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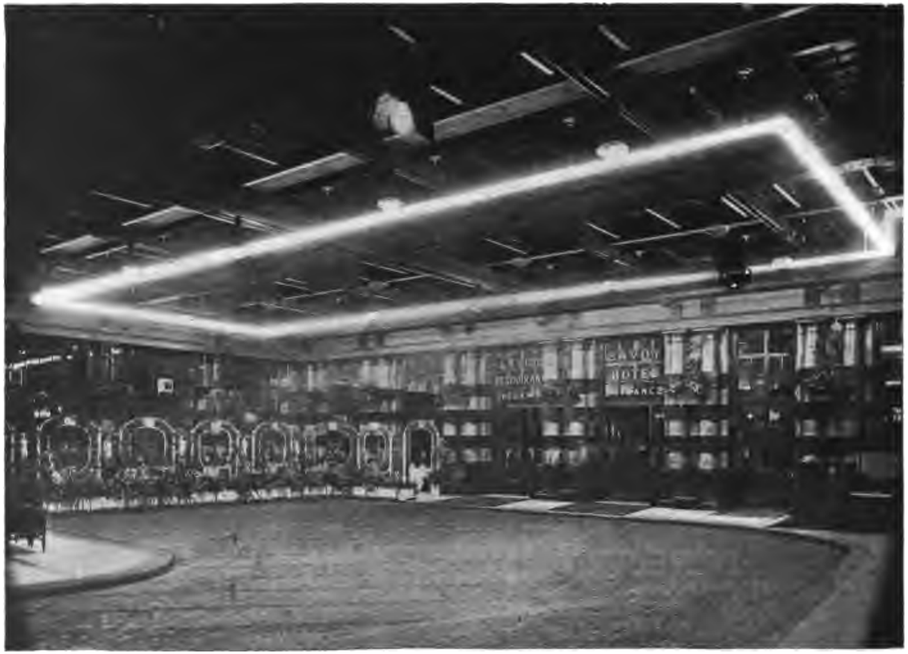

MOORE VAPOUR LAMP INSTALLATION AT THE SAVOY HOTEL (*see p.* 291).

From "The Illuminating Engineer.")

[*Frontispiece.*

ELECTRIC LAMPS

BY

MAURICE SOLOMON, A.C G.I., A.M.I.E.E.

NEW YORK
D. VAN NOSTRAND COMPANY
23 MURRAY AND 27 WARREN STREETS
1908

To

THE MEMORY OF

PROFESSOR W. E. AYRTON, F.R.S.

WHOSE DEATH HIS OLD STUDENTS DEEPLY DEPLORE

IN GRATEFUL REMEMBRANCE

OF THE TEACHING WHICH FIRST AWAKENED AN INTEREST IN

THE SUBJECT OF THIS BOOK AND TO WHICH

ANY MERITS IT MAY POSSESS

ARE DUE

PREFACE

In the following pages I have made no attempt to describe any electric lamps other than those which have been proved to be of commercial use: enough may be written about these to fill a book; an adequate account of those which either have not advanced beyond the laboratory stage or only exist in the fond imagination of their inventors would require at least another volume.

With most of the lamps which have reached the commercial stage I can claim more than a bowing acquaintance as I have been engaged during the last eight years in their manufacture, in the making first of Nernst filaments, later of carbon filaments, and finally in the manufacture of arc-lamp carbons, with a brief digression into experimental work on metallic filaments. Most of the information given in this book has therefore been obtained first hand, and I would like to express my thanks to the directors of the General Electric Company and of Robertson Electric Lamps, Ltd., for their kind permission to publish information obtained in their service.

My thanks are also due to Mr. C. Wilson, of the Robertson Lamp Company, for supplying certain data, to Mrs. H. Ayrton, for kind permission to make use of some of the curves in her book on *The Electric Arc*, to Mr. W. Duddell, for lending some oscillograph records, and to the proprietors of *The Illuminating Engineer*, for lending the block of the "Moore" lamp, which appears as frontispiece.

Particularly I have to thank Mr. F. S. Spiers, for reading the manuscript and for much valuable criticism thereon, and Mr. H. E. Crocker, for assistance in some of the experimental work and in correcting the proofs.

References throughout the book have been given, as far as possible, to the English Technical Press as being easier of access to the English reader. Hence often where an article appeared originally in a foreign paper reference has been given by preference to a translation in one of the English papers.

It is my hope that the book may prove of use both to the user of electric lamps and the student of electrical engineering.

MAURICE SOLOMON.

45, Newhall Street,
Birmingham,
September 8, 1908.

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CHAPTER I

THE PRINCIPLES OF ARTIFICIAL ILLUMINATION

√ The object of artificial lighting should be to reproduce as closely as possible the natural illumination due to daylight. There are a number of exceptional cases to which reference will be made presently, but as a general rule the principle stated above should be the guide in all questions relating to artificial illumination and illuminants. It is necessary, therefore, to consider carefully the characteristics which distinguish daylight, and three can at once be recognised as being of primary importance: these are the distribution of the illumination, its intensity and its colour. It will be as well to put on one side at the outset the illumination due to direct sunlight, which, except for the additional beauty which it may confer upon scenery, is generally unsatisfactory. The inequality of the distribution, in this case so marked, is very much diminished in the case of diffused daylight. Nevertheless, such unevenness as remains is of great assistance to the appreciation of solidity and the realisation of distance, as is evidenced by the flat and uninteresting appearance of a landscape on a heavily clouded day when the diffusion is sufficient to mask effectually the direction

of the lighting. In interior lighting the original unevenness is increased by the inequalities introduced by the position of the windows. In a room lighted from above by a large skylight the conditions of the external illumination are most nearly reproduced; with the usual condition of windows in the walls the closeness of the reproduction depends naturally on the size and the position of the windows.

It may be remarked, however, that, although with diffused daylight the distribution of the lighting is uneven, the inequalities are small, and compared with those in all but the most perfect systems of artificial lighting are trifling. A little consideration will show that this is due to the comparative sizes of the sources of light. The larger the area of the source of light the more even is the distribution of the illumination which it produces, and it should be our aim, therefore, to produce artificial illuminants having as large light sources as possible. Unfortunately it is in this respect, almost more than in any other, that modern artificial illuminants are at fault, and the tendency is mostly towards the development of lamps having less light-giving area for the production of a given amount of light. It is satisfactory, however, to be able to say that the greatest promise of a nearer approach to the ideal is given by the recent developments of electric vapour lamps. Failing the possibility of utilising a light source of large area, recourse must be had to the expedient of using a large number of sources, each giving but a small amount of light, distributed in the space to be illuminated in such a way as to produce a fairly even distribution of light throughout. This gives rise to the necessity of producing lamps which shall give but little

light and which shall be of such a nature that they can be easily fixed in any desired position. To its adaptability in this respect the familiar electric incandescent lamp owes a very large measure of its success.

Of as much importance as the distribution is the intensity of the illumination. The eye is able to adjust itself, by the contraction or dilation of the pupil, to suit a very wide range of intensities, and we are fortunately able to see and distinguish objects with equal ease under very different conditions. Nevertheless, limits exist, and it is a familiar fact that the illumination may be either too intense or too feeble for ease or practicability of vision. It is important to realise that artificial illumination may as easily fail by providing too much light as by providing too little. Once a certain intensity of illumination has been produced the addition of more light may often spoil instead of improving the effect. The reason is not far to seek: though the eye can adjust itself to suit many intensities, it cannot be adjusted for two different intensities at the same time. Unless, therefore, the prime requirement of approximately even distribution is realised, the eye, as it turns from one direction to another, is obliged to readjust itself to suit the new conditions. This not only produces fatigue and is injurious, but directly defeats the whole object of the illumination. When the eye turns from the darker to the brighter places the expanded pupil admits too much light and momentary dazzling results. On turning from the bright places to the dark the contracted pupil admits too little light and it is impossible at first to see distinctly. This evil is enormously intensified by the fact that in general it is difficult to keep the light sources

themselves wholly out of the range of vision, and the eye is consequently intermittently directed towards them. Electric lighting, with its intensely bright light sources, must be admitted to be particularly blameworthy in this respect.

The limitations set by the costliness of artificial lighting must prevent us, however, from being too critical. Desirable though it may be that the lighting should be such as to produce approximately even illumination of sufficient intensity throughout the whole sphere of vision, it is often necessary to be content with the desired intensity locally, at the particular place required, and a much more moderate general illumination. For example, for reading or writing, the lighting may be so arranged that only the page is illuminated to the necessary intensity: nevertheless, the rest of the room should not be in darkness unless the eyes are literally never raised from the work, and the ideal condition will only be attained when the illumination of the rest of the room is the same as that of the work. It is to attain this object that the cheapening of the cost of artificial lighting is so desirable; we do not want so much to be able to indulge in more light where we use it as in more light where we do not use it.

The third characteristic of daylight which it is desirable to be able to reproduce fairly closely with artificial lighting is its colour. Sunlight or diffused daylight is spoken of as being white, but it is difficult to assign any exact meaning to this expression. The spectroscope shows that white light may be analysed into an infinite number of monochromatic lights extending over the complete range of the visible spectrum, the individual colours varying from a deep red to

a deep violet. As it is possible to measure the intensity of the radiation at any part of the visible spectrum, it would perhaps be feasible to define a standard spectrum as corresponding to white light, though it is doubtful if any useful purpose would be served thereby. For it is known that the impression of white light can be produced by the admixture of light of three different colours without the necessity of producing all the colours present in the solar spectrum. Nor is it by any means necessary that artificial light should be truly white. Colours may appear somewhat different by artificial light, but if the distortion is not great this is generally a matter of secondary importance. For special purposes, as for example the lighting of a picture gallery or of a manufactory of coloured materials, it may indeed become of the first importance, but such cases are exceptions. Usage, on the other hand, has so accustomed us to the warmer tones of artificial light, richer as it nearly always is in red and yellow rays, that it is an open question whether the exact reproduction of daylight would be regarded as at all a welcome innovation, especially by those who find their pleasure in the theatre or ball-room. Nevertheless, too wide a departure from white light must be avoided, and the colour difficulty alone forms the principal obstacle to the more general adoption of one of the most promising of all artificial illuminants, the mercury-vapour arc.

It is unnecessary to discuss in further detail the characteristics of daylight. Suffice it to say that the ultimate criterion by which all attempts at artificial lighting must be judged is the nearness with which they reproduce the light to which we are naturally accustomed. The most

important consideration, the magnitude of which causes it to overshadow all the rest, is the question of cost. Daylight costs nothing; the illuminating engineer strives more than for anything else to approach this ideal, and almost any defect would be forgiven if he could attain it. The first test to be applied to all artificial sources of light is the test of the cost of the illumination produced by their use, and this factor, more than any other, will govern their success. The true determination of the cost of lighting with any particular illuminant is a matter of great difficulty, since so many subsidiary and indeterminate factors enter into the calculation. This is especially the case when illuminants of different kinds are compared. The incandescent gas mantle, for example, which is probably the cheapest light source (in this country) for lighting small interiors, in the actual cost of production of light, loses much, if not all, of its advantage when healthiness, cleanliness and convenience are also considered. In comparing illuminants of the same kind, which is all that will be necessary in this book, the problem is considerably simplified, and it is possible to arrive at fairly accurate estimates of their relative merits. But even here there are many points of view to be considered, as will become evident when the different types of electric lamps are discussed in subsequent chapters.

It has been mentioned that there are a number of special cases for which artificial illumination is required where the reproduction of the illumination due to daylight cannot be aimed at as the ideal. It will not be necessary to enumerate these in detail, as numerous examples will occur to the reader. One or two instances of special importance

may be quoted. In almost all cases electric lamps of one type or another have proved particularly suitable for this class of work, and their adaptability has given rise to numberless special applications.

The use of very powerful electric arcs for searchlights has become a very important feature of naval tactics. These arcs do not differ from the ordinary arc light of our streets except in the strength of current used and the large sizes of the carbons consequently required. The number of carbons used annually by the British Navy for this purpose is, even in peace time, very large, and the writer will perhaps be excused for referring in this connection to the importance of this fact as an argument in favour of the maintenance of the industry of carbon manufacture in this country. Arc lamps similar in power to naval searchlights are used also to a limited extent for lighthouse work.

Theatre lighting is another instance of special lighting for which electric lamps are far superior to other light sources. The brilliant and often highly artistic effects with which the present day public is familiar would be unattainable by any other means. As an example of a similar kind may be mentioned the display illumination which now forms an inseparable feature of all exhibitions. Results of great beauty have been obtained by the use of electric lamps for this purpose, the most recent really striking examples which have been produced in Europe being the illumination of the Chateau des Eaux at the 1900 Paris Exhibition, and of the Court of Honour at the Franco-British Exhibition.

Finally, reference may be made to the use of electric lamps for medical purposes, as in the treatment of lupus by

ultra-violet light, the use of Röntgen rays and other cases. These are, however, only collateral developments of electric lighting, and great as their benefit has been to mankind, they cannot count as an attainment of the primary aim of the maker of electric lamps, the economical production of artificial illumination.

CHAPTER II

THE PRODUCTION OF ARTIFICIAL LIGHT

ARTIFICIAL illuminants divide themselves into two groups according as the light emission is due to incandescence or to luminescence, or, to use common but less scientific terms, according as the light source is a hot or a cold light. At the present time all the artificial illuminants of any practical value, with possibly the exception of electric vapour lamps, are incandescent bodies, and it is worthy of remark that the only natural light source of value also owes its origin to incandescence. When a body is heated it begins to radiate energy into the surrounding space. Investigation has shown that the energy is radiated in the form of waves in the æther. These waves travel forward with a definite velocity, v, of 186,000 miles per second. The distance between the crest of one wave and that of the next is called the wave-length, λ, and the number of waves passing any given point per second the frequency of vibration, n. It is obvious, when λ and v are both expressed in the same units, that

$$v = n\lambda.$$

It is found that when the temperature of the heated body is low the radiation consists only of waves of great length, which, whilst capable of affecting us with the sensation of warmth, are unable to produce on our eyes the impression of light. As the temperature is raised shorter waves are

produced, and after a time waves capable of producing the impression of red light are emitted, the body now becoming clearly visible as a source of light. At the same time the longer waves do not disappear but are in fact increased in intensity. The body has become light-giving by the addition of waves of a length capable of affecting the eye, but still continues to emit all the longer waves which are useless for illumination. As the temperature is still further raised more and more of the shorter waves are added

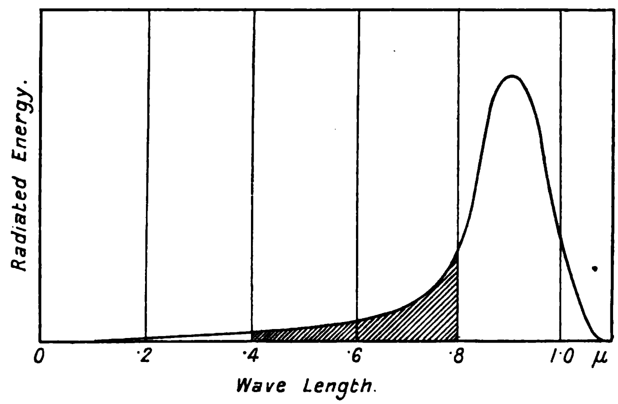


FIG. 1.—Energy radiated by a light source and wave-length.

and the colour of the emitted light changes through the well-known cycle from dull red to bright red, from bright red to reddish yellow, and so forth, until at a very high temperature it is a clear white. If the spectrum be now examined it will be seen to resemble fairly closely that of sunlight, but most important differences will be found if the amount of energy which is being radiated at each particular position of the spectrum is measured. In Fig. 1 is shown the general form of a curve representing the energy

radiated for each wave-length, the abscissæ representing wave-lengths ($\mu = \frac{1}{1000}\ m/m$)[1] and the ordinates the radiated energy. This curve, which is simply diagrammatic, has been drawn so as to bring out clearly the essential points to be observed. The eye is only sensitive to radiation having a wave-length lying between 0·4 μ and 0·8 μ. Waves having a length less than 0·4 μ are ultra-violet waves and waves having a length greater than 0·8 μ are infra-red waves. The former can be recognised by their chemical action and the latter by their thermal action, but neither can produce in the eye the sensation of light. That portion of the curve lying between these limits is shaded, and the area of the shaded portion represents, therefore, the total amount of energy perceptible as light, the area of the whole curve representing the total energy radiated. With all artificial illuminants the luminous efficiency[2] is much smaller than here shown, as will be seen from the curves and data to be given presently.

In order to determine the laws governing the relations between radiation and temperature use has been made of an ideal conception called the perfectly black body. The necessity for this conception is easily understood. If we have two bodies A and B at a given temperature inside a closed opaque vessel which is maintained at the same

[1] This unit is called a *micron*.

[2] By luminous efficiency is understood the ratio of the energy radiated within the limits of the visible spectrum to the total energy radiated. This is sometimes called the radiant efficiency, the expression luminous efficiency being used for the ratio of the energy radiated within the limits of the visible spectrum to the total energy dissipated by the light source, including therefore that dissipated by convection, conduction, etc.

temperature, then no alteration of the temperature of either A or B will take place. It follows, therefore, that the radiation emitted by A and absorbed by B in a given time must be equal to the radiation emitted by B and absorbed by A. This must be true not only of the total radiation but also of the radiation of each particular wave-length, since no alteration of temperature would occur if the bodies were separated by a medium allowing only radiation of one particular wave-length to pass. Hence we arrive at the conclusion that if two bodies are at the same temperature the radiation emitted by the first and absorbed by the second must be equal to that emitted by the second and absorbed by the first, both in total amount and in the intensity and wave-length of every part. Further, it must be true that the intensity of the radiation increases with the temperature not only for the total radiation but also for the radiation of each wave-length. Suppose now that the body A is of carbon which absorbs nearly all the radiation falling upon it, whilst the body B is of glass which transmits a large proportion. Then the amount of radiation emitted by the carbon and absorbed by the glass is small, but as the carbon absorbs all the radiation falling on it from the glass it follows that the amount of radiation emitted by the glass must be small. Let E_c and E_g be the energy emitted by the carbon and glass bodies respectively, and A_c and A_g their coefficients of absorption. Then we have

$$E_c A_g = E_g A_c$$

$$\text{or } \frac{E_c}{A_c} = \frac{E_g}{A_g} = \text{constant.}$$

Now let there be introduced into the same vessel a perfectly

black body, that is to say, a body which absorbs the whole of the radiation falling upon it. Let E_b be the amount of energy radiated by this body and A_b its coefficient of absorption. Then

$$\frac{E_c}{A_c} = \frac{E_g}{A_g} = \frac{E_b}{A_b}$$

but $$A_b = 1$$

therefore $$\frac{E_c}{A_c} = \frac{E_g}{A_g} = E_b,$$

or in general for any body

$$\frac{E}{A} = E_b \quad . \quad . \quad . \quad . \quad . \quad (1)$$

If we call the quantities as above for a particular wave-length λ, E_λ, A_λ and $E_{b\lambda}$ respectively, we have

$$\frac{E_\lambda}{A_\lambda} = E_{b\lambda} \quad . \quad . \quad . \quad . \quad . \quad (2)$$

It is apparent, therefore, that we can study the laws governing the alteration of radiation with temperature for all bodies by studying these laws for a perfectly black body, since such a body affords a standard for comparison. Equations (1) and (2) show that the total radiation and the radiation of any particular wave-length from a given substance at a given temperature is equal to the corresponding radiation from a perfectly black body at that temperature multiplied by the coefficient of absorption for the given substance at the given temperature.

No known substance answers the requirements of a perfectly black body, since all reflect a portion of the radiation falling upon them. It is, however, possible to construct an apparatus the radiation from which shall correspond to that

from the ideal substance. Such an apparatus is shown in Fig. 2, and consists simply of a tube completely closed at one end and closed at the other end with the exception of a small opening O. Any radiation which enters the tube at O will be either absorbed by the walls of the tube or confined to the inside of the tube by repeated internal reflections. A small percentage may after reflection find its way out again through O, but if the internal volume of the tube is large and the area of the opening O is small this percentage becomes negligibly small. The inside of such a tube, since it absorbs the whole of the radiation falling upon it, is a perfectly black body, and the radiation from it passing out through O must be the same as the radiation from such a body. If means be provided for heating the tube to any desired temperature, electrically or otherwise, and for measuring the temperature inside the tube, which may be done by an electrical thermometer inserted in the tube, the laws governing the radiation from a black body may be determined.

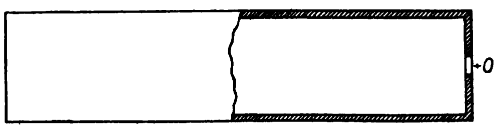


FIG. 2.—Experimental black body.

By the use of this apparatus Lummer and Pringsheim have demonstrated the correctness of the law of Stefan and Boltzmann that the total energy radiated by a black body is proportional to the 4th power of the absolute temperature. The following table shows how closely the calculated and observed results agree between the limits 373° Abs. and 1,535° Abs. (100° C. and 1,262° C.).

This table shows in the first column the absolute

temperature of the experimental black body as observed, and in the second column the same temperature calculated according to the Stefan-Boltzmann law from the measurement of the radiated energy. The third column shows the difference between the two values thus obtained.

TABLE I.

Absolute Temperature Observed.	Absolute Temperature Calculated.	Difference.
373·1°	374·6°	− 1·5°
492·5	492·0	+ 0·5
723·0	724·3	− 1·3
745	749·1	− 4·1
810	806·5	+ 3·5
868	867·1	+ 0·9
1,378	1,379	− 1
1,470	1,468	+ 2
1,497	1,488	+ 9
1,535	1,531	+ 4

We have therefore, if $E_{b\lambda}$ be the energy radiated, for the wave-length λ

$$\int_{o}^{\infty} E_{b\lambda} . \, d\lambda = C \, T^4$$

where C is a constant and T the absolute temperature.

$$\text{Or} \qquad E_b = \int_{o}^{\infty} E_{b\lambda} . \, d\lambda . = C \, T^4 \qquad (3)$$

In Fig. 3 are given the curves obtained by Lummer and Pringsheim for the relation between the energy radiated and the wave-length for a black body at different temperatures. It will be observed that these curves indicate that the wave-length for which the amount of energy radiated is a maximum becomes shorter and shorter as the temperature is increased. For example, the maximum of the curve for

998° is at 3μ, for 1,259° at $2{\cdot}3\mu$, and for 1,646° at $1{\cdot}8\mu$. Investigation has shown that definite relations, known as Wien's radiation laws, connect the absolute temperature, the wave-length corresponding to the maximum radiation, and the amount of energy radiated for that wave-length. If T, λ_m and E_m denote these quantities the following relations hold

$$\lambda_m T = \text{constant, A} \quad . \quad (4)$$
$$E_m T^{-5} = \text{constant, B} \quad . \quad (5)$$

or in words, the product of the wave-length corresponding to maximum radiation and the absolute temperature is a constant, and the maximum radiation is proportional to the 5th power of the absolute temperature. In Table II. are given the results of Lummer and Pringsheim's measurements, which confirm the accuracy of these laws between the limits 620° Abs. and 1,646° Abs. (347° C. and 1,373° C.).

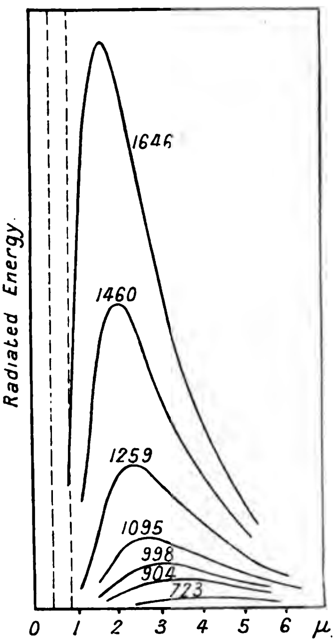


FIG. 3.—"Black-body" Radiation at different temperatures. (*Lummer and Pringsheim.*)

It will be seen that the value of the constant $A = \lambda_m T$ was found to be 2,940.

From what has been said it is clear that at any given temperature the perfectly black body radiates the greatest possible amount of energy. It by no means follows that it

is therefore the most suitable for the purposes of artificial lighting. The only radiated energy which is perceptible as light is radiated between the limits 0·4 μ and 0·8 μ, and the amount of visible energy radiated is therefore given by the expression $\int_{0\cdot4\mu}^{0\cdot8\mu} E_{b\lambda} \cdot d\lambda$, and not by the expression in equation (3). It has been shown that the total energy radiated increases as the 4th power of the absolute

TABLE II.

Absolute Temperature.	λ_m.	E_m.	$\lambda_m T = A$.	$\frac{E_m}{T^5} = B$.
1,646°	1·78	270·6	2,928	2,246
1,460	2·04	145·0	2,979	2,184
1,259	2·35	68·8	2,959	2,176
1,094	2·71	34·0	2,966	2,164
998	2·96	21·50	2,956	2,166
908	3·28	13·66	2,980	2,208
723	4·08	4·28	2,950	2,166
621	4·53	2·026	2,814	2,190
Mean .	—	—	2,940	2,188

temperature: the law connecting the visible energy radiated is less simple.

Not only does the area of the curve between the limits of the visible spectrum increase according to a different law than that governing the increase of total area, but the radiations of different wave-lengths have very different values as far as their power of producing the impression of light is concerned. This is often expressed by saying that the luminosity of the different wave-lengths varies: thus a given amount of energy radiated as red light produces the

impression of much less light than the same amount of energy radiated as green light. It will readily be seen that this is only an extension of the fact that the infra-red and ultra-violet waves are not visible at all. In order to study the actual light emission from a given body curves must be drawn connecting the brightness of the light with the wave-length as well as curves connecting the energy radiated with the wave-length. Such luminosity curves would lie wholly within the range of the visible spectrum, and the laws governing their increase in area with increase in temperature are those required for the study of the variation in the amount of light given by a source with variation of its temperature.

Experiments by Lummer and Pringsheim have shown that the luminosity increases approximately as the 30th power of the temperature when the temperature is low (red heat) and less and less rapidly as the temperature rises, becoming finally proportional to about the 12th power. At temperatures corresponding to those usual in incandescent lamps the luminosity varies as about the 14th power of the temperature. The law of Wien, which shows that the position of the wave-length corresponding to maximum radiation shifts nearer and nearer to zero as the temperature rises, shows that if the temperature be increased beyond a certain limit (about 6,000°) further increase will be disadvantageous, the energy radiated shifting more and more into the ultra-violet region of the spectrum. Such temperatures are not, however, attainable in practice. It is desirable, therefore, if we are using a perfectly black body as a source of light that it should be raised to the highest temperature possible. Under these conditions it

will not only radiate the greatest amount of energy but it will radiate the highest possible percentage within the useful limits. What is true of the perfectly black body in this respect must also be true of all other bodies which give out light purely as a result of their temperature. With any given body, therefore, which is used as an artificial illuminant, the best result will be obtained when it is worked at as high a temperature as other considerations may render practicable.

It is, however, more difficult to answer the question whether the ideal illuminant should or should not approach the perfectly black body in characteristics. Suppose we have three bodies of equal surface area, such as carbon, glass and polished metal, the first of which absorbs nearly all radiation falling on it whilst the second transmits, and the third reflects, a large proportion. Let all three be raised to the same temperature. Now if, as we may assume for the moment is the case, the curves connecting energy radiated and wave-length have the same shape for each of the three substances, it is immaterial from the point of view of economy which is used as the source of light; whereas the energy radiated for equal surface will vary greatly, the percentage of this which is visible will be the same in each case. The carbon may be radiating energy which can be represented as 100, the glass as 20 and the polished metal as 50, and if in each case 2 per cent. of this is visible as light, the amount of light from the three sources will be 2, 0·4 and 1 respectively, but the luminous efficiency of all three is 2 per cent. To make matters clearer, suppose all the bodies are maintained at the given temperature by being heated electrically; then if the amount of electrical

power required to keep the carbon at the given temperature is 100 watts, the amounts required to keep the glass and the metal at the same temperature are 20 and 50 watts, since the amount of energy to be supplied must equal only that lost by radiation. Although much more light is obtained from the carbon, a corresponding greater amount of energy has to be supplied to produce it. It would seem, therefore, to be quite immaterial whether the bodies used as light sources are nearly approaching to black bodies or not. But there is another point of view to be considered: we are not only anxious to produce the light economically, we must also produce sufficient light. This is, however, merely a question of providing sufficient surface; if the area of the glass be increased five times and that of the metal doubled, then each will be radiating as much light as the carbon and all three will now require the same amount of electrical energy to maintain their temperature. It is, however, a distinct advantage, for reasons which have been pointed out in Chapter I. that the source of light should be as large as possible and its intrinsic brilliancy, or amount of light radiated from unit surface, as low as possible, and hence we see that bodies which are bad absorbers, which depart as far as possible from the black body, are preferable to those which approach it. For this reason a filament having a highly polished surface is to be preferred to one with a dull surface.

It must be clearly understood that what has been said above refers to bodies at the same temperature. It is sometimes asserted that a shiny filament is more efficient than a dull one for the following reason. If two filaments, the one polished and the other dull, both having the same

resistance and surface, be heated by currents of the same strength, each will dissipate the same amount of energy. The dull filament, since it radiates easily, will not attain a very high temperature, the total amount of energy supplied being dissipated at a low temperature. The polished filament, on the other hand, since it radiates less freely, will attain a much higher temperature before it is able to dissipate the energy supplied. The light from the polished filament will consequently be more economically produced than that from the dull filament, and will moreover be greater in amount. Apparently the polished filament is therefore a more economical light source. But this simply arises from the fact that it is being worked at a higher temperature. The dull filament can be made to give light just as economically by supplying more energy and increasing its temperature: when it attains the same temperature as the polished filament it will be giving more light, but by shortening its length the amount of light given can be made the same, when the amount of energy absorbed will also become the same. Any characteristics which enable the polished filament to be safely worked at a higher temperature than the dull one will, it is true, increase its value as a light source, but these have nothing whatsoever to do with the problems of radiation.

It has been assumed in the preceding argument that the different bodies all radiated energy in the same manner; that is to say, that the curves connecting radiated energy and wave-length were the same in all cases. This assumption is not necessarily true. In Fig. 4 are given three imaginary curves, A, B and C, which are supposed to represent to the same scale the radiation from unit area for different wave-

lengths from three bodies, A, B and C, at the same temperature. The body A is the perfectly black body and gives therefore the maximum possible radiation for each wave-length. The body B is supposed to be a poor radiator, such, for example, as a metallic filament with a highly polished surface; the radiation from this body is supposed to be for each wave-length proportional to the corresponding radiation from the black body, but less in amount. The

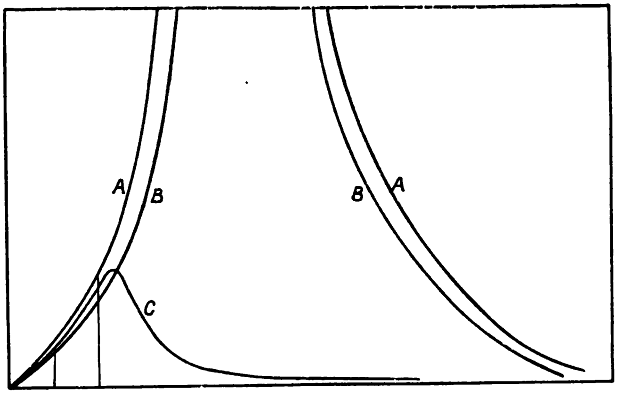


FIG. 4.—Radiated energy and wave-length for different light sources.

efficiency of the light given by B is, as already shown, the same as that given by the black body, though the total amount of light per unit area of surface is less. The radiation from C, on the other hand, is supposed to obey different laws to that from the black body. Whilst it is impossible that the radiation for any given wave-length shall be greater than that from the black body for the corresponding wave-length, there is no reason why it should not be less. In the imaginary case taken the radiation

has been supposed nearly equal to that from the black body over the range of the visible spectrum but very much less, over the rest of the spectrum. Whilst C is therefore emitting nearly as much light as the black body, it is emitting very much less energy in the form of non-visible (heat) radiation, and its luminous efficiency, which is measured by the ratio of the energy radiated within the limits of the visible spectrum to the total energy radiated, is consequently much higher.

It is at once evident that bodies of the type of C are precisely those which are most suitable as sources of light. By their use it would be possible to approach towards the ideal condition under which the whole of the energy radiated falls within the limits of the visible spectrum. Such bodies are said to possess the properties of selective emission. Unfortunately, amongst solid bodies, those which possess this property to any marked extent are rare. Nearly all incandescent solids and liquids give a continuous spectrum, but this in itself is not a proof that they may not be, to a certain extent, selective radiators, which can only be proved by measuring the radiation for each wave-length and finding whether it is or is not proportional to the corresponding black body radiation. On the other hand, the oxides of erbium and didymium give a continuous spectrum crossed by a number of bright bands; certain fused salts also have been found by Lenard to emit strongly coloured light when heated in the Bunsen flame. In these cases selective emission is present to such an extent as to affect the colour of the emitted light and be readily observable. But selective emission may exist as a diminution of the radiation of longer wave-length without affecting the colour of the emitted light, yet greatly

altering the efficiency of the body as a light-giving source. A certain amount of evidence has been obtained showing that most of the substances used as light sources in electric lamps possess the property of selective emission to a certain degree. But the experimental difficulties connected with these measurements are great and the evidence so far advanced cannot be considered very conclusive. It may be fairly certainly stated, however, that such differences as exist play but a small part in the efficiency obtained with different types of lamps in which an incandescent solid forms the source of light, and that it is temperature alone which determines their efficiency, that substance giving the most economical light which is capable of being run continuously at the highest temperature.

Various attempts have been made to determine the temperatures of the different sources of light, but the results obtained by different methods are not very concordant. The most satisfactory method appears to be to apply Wien's law connecting the temperature and the wave-length corresponding to maximum radiated energy, namely, that

$$\lambda_m \, T = 2{,}940,$$

from which we can obtain T when λ_m has been determined. In making use of this law it must be remembered that the radiation is assumed to follow the same laws as radiation from a perfectly black body, and moreover that the value 2,940 is the value of the constant for such a body. Since no body is perfectly black, this constant may have a different value for all ordinary illuminants. Lummer and Pringsheim determined its value for bright platinum to be 2,630. Hence, if we assume that the ordinary illuminants

lie in their behaviour somewhere between the perfectly black body and platinum, it is possible to obtain upper and lower limits for their temperatures. Lummer and Pringsheim, proceeding on this basis, have obtained the following results, the value of the temperature of the sun obtained in the same way being given for comparison :

TABLE III.

Type of Lamp.	λ_m.	Absolute Temperature.	
		Upper limit.	Lower limit.
Arc lamp	0·7 μ	4,200°	3,750°
Nernst lamp	1·2	2,450	2,200
Carbon-filament lamp . .	1·4	2,100	1,875
Sun	0·5	5,880	5,260

Electric lamps are not, however, confined to the use of solid bodies as sources of light. No lamps exist in which liquid bodies are used, and as liquids obey the same laws of radiation as solids it seems doubtful whether any development is to be expected on these lines. The use of gaseous light sources presents, however, much greater possibilities. The spectrum of the light from a gaseous source, as is well known, is not continuous, but is made up of a number of bright lines or bright bands. In some of these cases it is possible that the radiation is not simply a temperature effect, and the phenomena are rather those of luminescence than of incandescence, so that the laws which have been discussed must be applied with caution. Nevertheless, if the curve connecting the energy radiated with the wavelength be plotted for one of these sources, we have the same

criterion of the luminous efficiency, namely, the ratio of the area contained under the curve between the limits of the visible spectrum to the total area. In these cases, since selective emission is present to a marked degree, it is possible to attain high efficiency without the use of very high temperatures. The vacuum tube as applied in the Moore system, the mercury-vapour lamp, and, to a certain extent, the flame arc, are examples of the application of these principles to practical electric lighting.

It is of interest to say a word in reference to the actual value of the luminous efficiency of practical electric illuminants. Various attempts have been made to determine this by different methods and the results which have been obtained by different people are very far from being concordant. All, however, agree in showing that the luminous efficiency is extremely small, probably in the neighbourhood of 2 per cent. to 5 per cent. for incandescent electric lamps, and of 10 per cent. to 20 per cent. for arc lamps. If we take it that the best lamp yet made has not higher luminous efficiency than 20 per cent. we shall probably not be far wrong. In other words, under the best conditions, in order to produce a certain amount of light we are obliged to generate five times the amount of energy actually required, and generally ten or twenty times the amount. It is indeed fortunate that our eyes are sensitive to amounts of energy almost inconceivably small.

CHAPTER III

PHOTOMETRY

DEFINITIONS.

IN order to compare the relative values of different lamps it is necessary to be able to measure the light which they give. The study of this subject is known as photometry. There are five fundamental quantities used in photometry, namely, *quantity of light*, *luminous intensity*, *luminous flux*, *illumination* and *intrinsic brightness*. In no electrical subject, probably, does greater looseness of expression exist than in this, possibly because it is not of electrical origin. It will be well, therefore, to explain briefly what these quantities are before attempting their more careful definition.

Light is a form of energy. A source of light is a mechanism which converts energy supplied to it in some other form into radiant energy. As we have already seen, in most cases, only part of the radiant energy is capable of affecting our eyes; this part is light. A light source is thus radiating energy in the form of light, and the *quantity of light* emitted by the source depends on the rate at which it is radiating and the time during which it radiates. The conception of another quantity is thus introduced, the rate at which the source is radiating; this is called the *flux of light* or *luminous flux*. Its dimensions are those of energy divided by time, and it is, therefore, of the same nature as power. A source of light emits energy in all

directions in a sphere of which it is the centre. The energy need not be emitted equally powerfully in all directions; in some directions it may be greater than in others. We can express this fact by saying that the density of the flux or the *intensity of the light* can vary, and we can define the intensity as the flux emitted in a given solid angle divided by the angle. Intensity carries with it the idea of direction. To state the intensity of the light from a given lamp is to give the minimum of information as to its usefulness unless it be implied that the intensity is the same in all directions, or varies according to certain known laws. An equivalent intensity may, however, be given for the lamp by assuming the flux uniform and dividing it by the solid angle of a sphere; this quantity is called the mean spherical intensity and is the most important thing to know about a lamp. A practical light source is always of finite dimensions; its surface has a definite area. The intensity of the light emitted by a given surface of the source divided by the area of that surface measures the *brightness* or *intrinsic brightness* of the source. The source may be a true source of light, such as a lamp, or a secondary source, such as a surface receiving light from a lamp and reflecting it partly or wholly. In either case the brightness is measured in the same way. The *illumination* on a surface receiving light from a lamp, on the other hand, does not depend on the brightness of the surface. It depends simply on the luminous flux received by the surface, divided by the area of the surface; in other words, on the density of the flux received by the surface. The whole of the flux may be absorbed and the surface appear quite dark, or it may be reflected and the surface appear bright. In either case the illumination of

the surface is the same, it is only its brightness which varies. The expression "intensity of illumination" is sometimes used for illumination; its use is to be avoided, as it suggests that it connotes something different to illumination. Such a difference would exist if intensity of illumination were used for the quantity we have defined as illumination, and illumination used to express the whole flux falling on the surface, that is, the intensity of illumination multiplied by the area of the surface. But this is a quantity of little practical value, so it is better to avoid altogether the use of the expression "intensity of illumination."

With these few preliminary remarks we may proceed to a more exact definition of the various quantities and their units.

The *luminous intensity*, or more simply *intensity*, of a source of light is the most important quantity in photometry. It measures the intensity of the light given by the source in one direction. The unit of measurement is an arbitrary standard, *the candle*. The methods of reproducing the standard will be considered later. The intensity of a light source is expressed in terms of this standard as *candles* or *candle-power*. When a source of light is said to be giving 16 candle-power in a given direction it is meant that the intensity is the same as would be produced in that direction by 16 standard candles substituted for the actual source. The *mean horizontal candle-power* of a lamp is the mean of the values of the intensity measured in all directions in a horizontal plane through the (optical) centre of the lamp. The *mean spherical candle-power* is the mean of the intensities in all directions radiating from the source as centre. It is the intensity of an imaginary source giving

the same amount of light as the actual source but radiating with equal intensity in all directions. The *mean lower hemispherical candle-power* and the *mean upper hemispherical candle-power* are the means of the intensities in all directions below and above the horizontal plane respectively. The intensity is usually denoted by the letter I.

The *luminous flux* or *flux of light* is the quantity which measures the rate of radiation from the source. Unit flux exists when light is radiated with unit intensity in a beam of unit solid angle.[1] This unit is, however, rarely used; the *spherical candle-power* is used instead; it is the *total flux* when light is radiated with unit intensity in all directions, and is therefore 4π times the correct unit. Flux is denoted usually by the symbol Φ. Obviously $d\Phi = I\,d\omega$, and $\Phi = \int I\,d\omega$, which, when I is uniform throughout the sphere, becomes $\Phi = I\int d\omega = 4\pi I$. If Φ is expressed in spherical candle-power and I in candle-power, Φ is numerically equal to I for an uniform source.

The *illumination* produced by a source of light on any surface is the flux of light falling on the surface divided by its area. Its proper unit is, therefore, unit of flux per unit area. This illumination is produced by unit source at unit distance (when the unit flux is the correct unit and not the spherical candle-power which is 4π times too large). Illumination is usually defined, therefore, in terms of the source and the distance; the unit is called the *candle-foot.*

[1] For the benefit of those who have forgotten it may be mentioned that unit solid angle is the solid angle subtending unit area on the surface of a sphere of unit radius. It is called a *steradian*, but can hardly be said to be known by this name.

The expression is barbarous but in general use. It is the illumination produced by one candle-power at a distance of one foot. Illumination is denoted generally by the symbol E. When the flux falling on area d S is $d\,\Phi$ we have $\mathrm{E} = \frac{d\,\Phi}{d\,\mathrm{S}}$.

Intrinsic brightness, or simply *brightness*, is the candle-power emitted normally by unit area of the source. It is denoted by the symbol i and when I is the candle-power emitted by area d A of the source we have $i = \frac{\mathrm{I}}{d\,\mathrm{A}}$. It is measured in candle-power per square inch. The quantity is not frequently used, but its importance is gradually obtaining recognition. The intrinsic brightness of a lamp is the property which, when high, is most harmful to the eyes. The brightness of an illuminated surface is the property which enables it to be seen; as already pointed out this depends on the illumination and the nature of the surface. Hitherto engineers have been content to provide the illumination and leave the other considerations in other hands. They are beginning to realise that this can no longer be done satisfactorily, and that in determining the amount of illumination to be provided in a room they must take more scientific consideration of the owner's taste in wall-papers.

The *quantity of light* produced by a source is the product of the luminous flux and the time during which the flux is produced. Its unit is the *spherical-candle-power-hour*, or the *spherical candle-hour*. It is given in terms of the flux Φ and the time t by the equation $\mathrm{Q} = \Phi\, t$. The name of the unit is usually shortened to *candle-hour;* there is good justification for this. The flux of light from a lamp having a mean spherical candle-power of 16 is 16 spherical candle-

power. In one hour such a lamp gives 16 spherical-candle-power-hours of light. The lamp, however, gives as much light in one hour as 16 candles would give (if, which is not the case, the flux from a candle was uniform in intensity); there is therefore good reason for calling this amount of light 16 candle-hours. It suggests at once a concrete value for the light. Sixteen spherical-candle-power-hours suggests nothing.

The units which have been given above are those most generally to be found in English literature. They are far from satisfactory; their names are made up by combinations of words too ugly to be used, and the incorrect unit of flux involves the unnecessary introduction of 4π, and a complication in the definition of the unit of illumination. A more scientific set of units was proposed by the Geneva Congress of 1896. They are all derived, like the units already defined, from the standard candle. Unfortunately, the English, German and French standard candles are all different. The standard proposed to be used was the Violle unit, which will be described later. This is at present very hard to reproduce, and in the meantime the German standard, the hefner, is generally used as the basis of the system. This is a matter of secondary importance. The units could all be used without discarding the English standard candle as the basis, which English lamp-makers are loth to do, as the English candle is a bigger unit than the hefner, which is a useful fact when disparaging criticisms are made. For precision the word "English" could be prefixed to the name of each unit just as it must always be prefixed to the word "candle" if precision is desired. The units proposed are the following:—

Luminous Intensity.—The *candle, bougie decimale*, or *pyr*, equal to $\frac{1}{20}$ of the Violle platinum standard. The pyr has been determined as equal very nearly to 1 hefner, or 0·915 English candles.

Luminous Flux.—The *lumen*, equal to the flux of light from 1 pyr in unit solid angle. The lumen is *not* a spherical pyr. The lumen equals $\frac{1}{13 \cdot 8}$ spherical-candle-power.

Illumination.—The *lux*, equal to the flux of one lumen per square metre. The unit of flux being correct, the lux is also equal to the illumination produced by 1 pyr at a distance of 1 metre. It is approximately $\frac{1}{12}$ of a candle-foot.

Brightness.—The pyr per square centimetre. The unit has no special name. It is equal to 5·9 candles per square inch.

Quantity.—The *lumen-hour*, equal to the flux of one lumen for one hour. It is equal to $\frac{1}{13 \cdot 8}$ candle-hours.

Fundamental Laws.

Suppose we have a source of light O (Fig. 5), so small that it can be regarded as a point, emitting light in the direction O A of uniform intensity I throughout a cone of solid angle $d\,\omega$. The flux of light $d\,\Phi$ is given by—

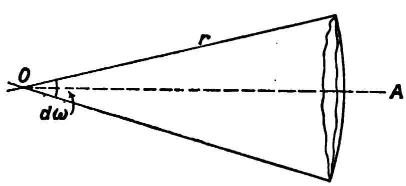


Fig. 5.—Light radiation from a point source.

$$d\,\Phi = \mathrm{I}\,d\,\omega.$$

Let r be the radius of a sphere having its centre at O.

Then $r^2\, d\,\omega$ is the area cut off on this sphere by the cone, and the illumination on this surface is

$$E = \frac{d\,\Phi}{r^2\, d\,\omega} = \frac{I\, d\omega}{r^2\, d\,\omega} = \frac{I}{r^2};$$

or the illumination produced by a given source of light on a surface normal to the incident radiation is directly proportional to the intensity of the light in the direction of the surface, and inversely proportional to the square of the distance of the surface from the source.

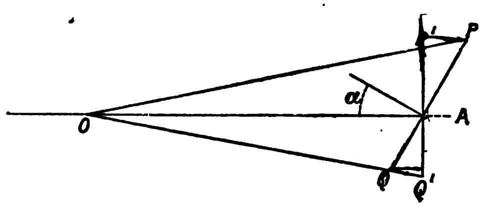


FIG. 6.—Illumination on an inclined surface.

If the element of surface is inclined to the incident ray (Fig. 6), the normal to the surface making an angle a with the incident ray, we have, if d S is the area of the actual surface P Q, and $d\,s$ the area of the projection P′ Q′ on a plane perpendicular to the incident ray,

$$d\,s = d\,S \cos a,$$

and the illumination on the inclined surface is

$$\begin{aligned} E' &= \frac{d\,\Phi}{d\,S} \\ &= \frac{I\, d\,\omega \cos a}{d\,s} \\ &= \frac{I\, d\,\omega \cos a}{r^2\, d\,\omega} \\ &= \frac{I \cos a}{r^2}; \end{aligned}$$

or the illumination produced by a given source of light on a surface whose normal makes an angle a with the incident

ray is directly proportional to the intensity of the light in the direction of the surface and to the cosine of the angle a, and inversely proportional to the square of the distance of the surface from the source.

If, instead of a point source of light, we have a source of area $d\,S'$ emitting light normally with an intrinsic brightness i, we have by definition

$$I = i\,d\,S'.$$

If we measure the light in a direction not normal to the surface, but making an angle a' with the normal, it is found that the intensity is equal to

$$I \cos a' = i\,d\,S' \cos a'.$$

This law, which is experimentally true, is known as the law of cosines, and is of considerable importance in dealing with the light from arc lamps.

Photometric Methods.

All methods of photometry are dependent upon the laws just deduced, and upon the fact that, although the eye is unable to measure the brightness of a surface, it is able to judge with tolerable accuracy when two surfaces are equally bright. The eye is able to judge with still greater accuracy when the difference in brightness between two surfaces is equal to the difference in brightness between two other surfaces, or in other words to judge equality of contrast. It is worth while mentioning the fact that the eye does not judge equality of illumination, though this is generally stated to be the case. The two illuminated surfaces compared in photometric measurements are deduced to be equally illuminated, on the assumption that their reflecting properties are the same, and correction for the inaccuracy

of this assumption has to be made in all measurements of precision. A photometer consists essentially of a standard lamp with which to compare the lamp under test, the test lamp itself, and the two surfaces illuminated respectively by the two lamps. The relative positions of these three parts are adjusted until the brightness of the two illuminated surfaces is the same, when from the laws governing their illumination the relative intensities of the lamps can be deduced. In the majority of cases the two lamps are mounted at opposite ends of an optical bench, and the surfaces to be illuminated are mounted on a carriage between the two; one of the three is then moved to and fro until the position of balance is obtained. This arrangement is convenient, but, of course, not essential. The part of the photometer containing the two illuminated surfaces is generally called the photometer *screen* or *head*. Numerous types of screen have been devised, but we shall only describe a few typical and important examples here. For further information, Palaz' "Treatise on Photometry" or Liebenthal's "Praktische Photometrie" may be consulted, as well as recent contributions to the scientific and technical journals.

Photometric measurements do not admit of very great accuracy, partly because the sensitiveness of the eyes of different observers differs and partly because, even under the best conditions, the eye cannot appreciate differences of brightness less than about $\frac{1}{2}$ per cent. A single observer may obtain results agreeing within 0·5 per cent., but the results obtained by different observers at different times rarely agree to within less than 2 per cent., even when the greatest possible care is taken to ensure accuracy.

In commercial work an accuracy better than about 5 per cent. is hardly necessary, even if so great an accuracy as this is required. The photometry of incandescent lamps, as carried out by girls under the conditions of workshop practice, is effected with remarkable rapidity and extraordinary accuracy, considering the circumstances. It is hardly necessary to point out that the most accurate photometer is not necessarily the most suitable for commercial lamp testing.

The Rumford Photometer.—In Fig. 7 is a diagram representing the principle of the Rumford photometer, one of the oldest, simplest, and best of all photometers. L_1 and L_2 are the two sources of light to be compared, and A B is a vertical white screen. Between the lamps and the screen is a vertical rod R. The lamp L_1 will throw a shadow of this rod on the screen at L'_1 and the lamp L_2 a shadow at L'_2. The shadow L'_1 is illuminated only by light from L_2, the illumination being equal to $\frac{I_2}{d_2^2}$ where I_2 is the intensity of the light from L_2 in the direction L_2 L'_1 and d_2 the distance L_2 L'_1. Similarly, the illumination of the shadow L'_2 is equal to $\frac{I_1}{d_1^2}$. By moving one lamp to or from the screen, the illuminations of the two

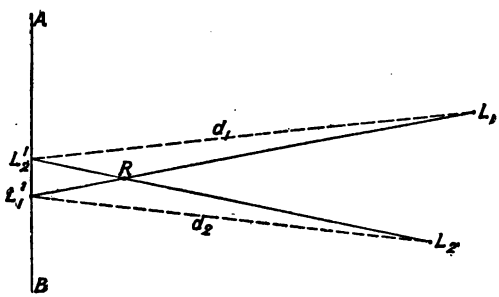


FIG. 7.—Principle of the Rumford Photometer.

shadows can be made equal, each shadow then appearing equally intense. We then have

$$\frac{I_1}{d_1^2} = \frac{I_2}{d_2^2},$$

and if d_1 and d_2 are measured and the intensity of I_2 is known, we have

$$I_1 = \frac{d_1^2}{d_2^2} I_2.$$

With care very accurate results indeed can be obtained with the Rumford photometer in spite of the fact that it

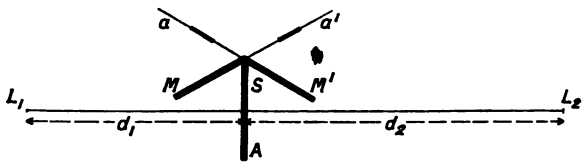


FIG. 8.—Principle of the Bunsen Photometer.

does not look like a scientific instrument. Almost the only disadvantage is the relative position of the lamps and the screen, which is not very convenient. Against this must be set its extreme simplicity, the absence of all the troublesome sources of error which more complicated apparatus introduces, and the fact that it is practically independent of stray light from other sources falling on the screen.

The Bunsen Photometer.—This photometer is based on the principle that a spot of grease on a sheet of paper appears bright on a dark ground when illuminated from behind and dark on a bright ground when illuminated from in front.

In Fig. 8 is shown diagrammatically the general arrangement used with a Bunsen photometer. The screen A, consisting of a white sheet of paper with a central, circular or

star-shaped, grease-spot, is mounted on a carriage running on a photometer bench, at the two ends of which are the lamps to be compared, L_1 and L_2. The light from L_1 falls on the left-hand side of the screen, and that from L_2 on the right-hand side. Behind the screen are fixed two mirrors, M and M′, which form images of the screen at a and a', thus enabling an observer in front to see both sides of the screen at once. It is obvious that the images of the spots are somewhat far apart and are separated by the shaded images of the part S of the screen. This renders comparison rather difficult, and several modifications, which need not, however, be described here, have been introduced into the photometer head which overcome this difficulty.

In order to obtain the position of balance with the Bunsen screen, the photometer head is moved to and fro until one or other of the following positions is reached:—

(1) That in which the spot vanishes in the left-hand image.

(2) That in which the spot vanishes in the right-hand image.

(3) That in which the spot appears in each image to stand out equally clearly from the background.

If the ratio of the squares of the distances $\frac{d_1^2}{d_2^2}$ be found to be c_1, c_2 and c_3 respectively for these three positions, it is easy to show that

$$I_1 = \sqrt{c_1 c_2}\, I_2,$$

and
$$I_1 = c_3 I_2,$$

on the supposition that both sides of the screen are identical. This is rarely the case, and for accurate work means should exist for reversing the screen and fresh positions of balance

obtained for which the ratio $\frac{d_1^2}{d_2^2}$ is c'_1, c'_2 and c'_3 respectively. Then it can be shown that

$$I_1 = \sqrt[4]{c_1\, c'_1\, c_2\, c'_2}\, I_2$$

and
$$I_1 = \sqrt{c_3\, c'_3}\, I_2.$$

For rough work c_3 and c'_3 may be assumed equal and the value of I_1 obtained by one measurement only by the third method.

Modifications of the Bunsen screen are those known as the Elster and Joly screens. In the Elster screen two translucent blocks are fixed together as in Fig. 9, separated by an opaque sheet A B. In the Joly screen the two blocks are fixed together without any separating sheet. In both cases balance is obtained by shifting the screen until the illumination of the faces F_1 and F_2 appears equal. For accurate work differences in the blocks should be eliminated by reversing the screen and taking the mean of the two results obtained.

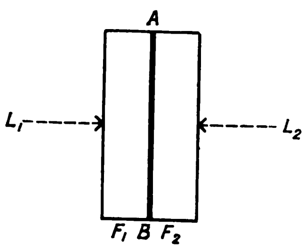


FIG. 9.—Elster Photometer Screen.

Lummer-Brodhun Screen.—This is a very accurate form of photometer screen, the arrangement of which is shown diagrammatically in Fig. 10.

An opaque screen A, white on both sides, is fixed perpendicularly to the line joining the two sources of light. The light is reflected from the two sides of the screen through two totally reflecting prisms M_1 and M_2 to the Lummer-Brodhun prism PQ. This consists of two right-angled

prisms placed base to base. The prism P has part of its hypothenusal face ground down as shown, the central part being in optical contact with the hypothenusal face of Q. The light reflected from M_1 passes through P, and where the surfaces of P and Q are in contact through Q to the observing telescope, T. That falling on the part of the base of P not in contact with Q is reflected back and does not

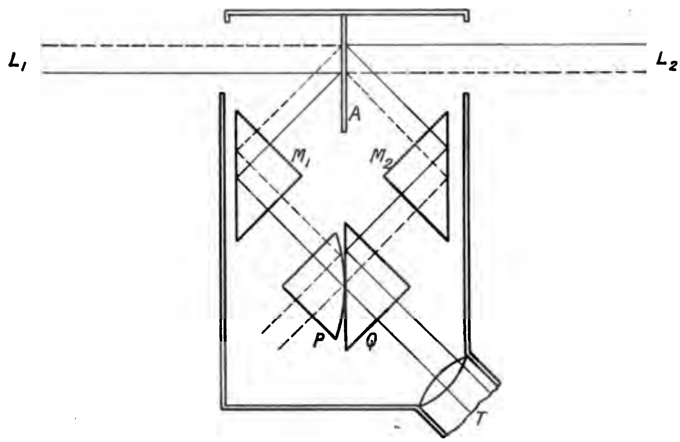


FIG. 10.—Lummer-Brodhun Screen.

reach the telescope. The light from M_2 is totally reflected from the base of Q to the telescope, except where Q is in contact with P, where it passes through P and is lost. In the figure the full lines show on each side the course of the rays which finally reach the eye, and the dotted lines the course of the rays which are lost. There is, therefore, seen in the telescope an illuminated disc, the centre of which is illuminated by light from L_1 and the outer ring by light from L_2. The edge between the two images is

perfectly sharp, and the position of balance at which this disappears and the whole field appears evenly illuminated can be obtained with great accuracy. Reversal should always be employed in order to eliminate errors due to inequalities in the two sides of the screen. By a slight modification in the prisms, this photometer screen can be converted into a contrast screen giving two images as in Fig. 11, the position of balance being obtained when the contrast is equal on both sides. With this method the accuracy is higher than with the method of equal illumination.

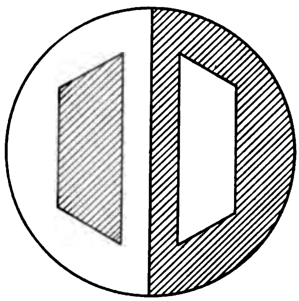


FIG. 11.—Image from Lummer-Brodhun Contrast Screen.

The Lummer-Brodhun photometer head is a complicated arrangement and possesses several disadvantages as a result. When the number of surfaces which the light encounters, and the prisms through which it passes, are remembered, it is easy to see that there is plenty of opportunity for errors to be introduced. In addition the screen has to be observed through a telescope which is not at all a pleasant position in which to work. As Mr. Trotter has observed, photometry is ultimately a matter of judgment, and judgment is made most accurately when the mind is quite at ease. On the other hand, the judgment of equal illumination is particularly easy with this photometer head; the position of balance can be obtained with great sharpness even by an unpractised observer. This is a considerable advantage, especially to those who are not constantly making photometric measurements, and these

form the great majority. Familiarity and practice may enable an observer to obtain equally or even more accurate results with a Rumford screen, but the average electrical engineer prefers a photometer which he can use with precision the first time he tries it. An expert butcher can judge how much a live ox will weigh when cut up into beef to within 0·1 per cent., but this is not any reason for urging the abandonment of the steelyard.

Heterochromatic Photometry.

A difficulty occurs in photometry when the lights to be compared are of different colours. It is then found to be a much harder matter to judge when equality of brightness is obtained on the two illuminated surfaces. But, though difficult, it is not impossible; here, again, practice makes perfect, and, according to the best authorities, even two different pure spectral colours can be compared with as great accuracy as two lights of the same colour. Such an extreme case is not often met in ordinary work, but the developments of electric lamps necessitate the comparison of illuminations of very different tint. The light from an arc lamp, a Nernst lamp, or a tungsten lamp is of markedly different tint to that from a carbon-filament lamp. With any of the photometers already described, the ordinary observer will probably find it at first a troublesome matter to obtain the position of balance. In order to obviate these difficulties, special photometers have been devised. These have incidentally served to bring to the front two very important questions. The first is, whether it is possible at all to say that two illuminations of different

colour have the same brightness, and the second, whether it is the brightness which we really want to measure.

The answer to the first of these questions is, in the author's opinion, simple and in the affirmative. The question is purely one of fact, and, unless the statements of the most experienced observers, such as Sir W. Abney, Prof. Ayrton, Mr. Trotter, and others, are to be entirely discredited, it is impossible to doubt that illuminations of very different colours can be accurately compared for brightness. In the second place, the very phenomenon which lies at the root of this discussion cannot even be stated without assuming that illuminations of different tints can be compared. This is the Purkinje phenomenon, which is as follows:—If two surfaces be illuminated by light of two different colours, red and green, for example, then two positions can be found, for which, whilst the ratio of the distances of the lamps from the screen is the same, in one the green surface, and in the other the red surface appears brighter. It is at once obvious that if we are able to say the green surface is brighter in one case, and the red surface in the other, we must be able to find a position in which we can say the surfaces are equally bright. The equality of brightness may be difficult, but cannot be impossible, to judge. But whilst the Purkinje phenomenon helps to prove the assertion that the brightness of illuminations of very different colour can be compared, the question which it raises is of a somewhat different nature. To make this clear we will describe the experiment a little more fully. Two incandescent lamps, one with a red bulb and the other with a green bulb, are placed about 6 feet apart, and a photometer screen is placed between them in the position in which

the two sides appear equally bright. If the distance between each lamp and the screen be now halved, the red side will appear brighter; if the distances be doubled, the green side will appear brighter. In each of these two positions, suppose the position of balance to be obtained, and let G and R be the candle-power of the two lamps respectively. In one position we shall find that

$$G = k\,R,$$

and in the other position

$$G = k'\,R.$$

Which of these two coefficients, k or k', gives correctly the candle-power of the green lamp in terms of that of the red lamp? Or is it possible at all to express the candle-power of a lamp as a definite ratio of that of another lamp giving light of a different colour? It would seem at first that this is not possible. But the Purkinje phenomenon only occurs when the brightness of the two illuminated surfaces is low. It is a physiological phenomenon of importance only under these circumstances. If the brightness of the two surfaces is such as we are ordinarily accustomed to use in photometry the position of balance will be found to give the same value for k, whatever the distance between the lamps. When it is remembered, also, that we have hardly ever to deal in practical photometry with lights of such strongly different colours as the light transmitted through red and green glass, it will be seen that the Purkinje phenomenon does not really play an important part in photometry. Nevertheless, it is true that the phenomenon shows that the value for the candle-power of a given lamp is not an absolutely definite value. The candle-power of a lamp in a given direction is sixteen when it is radiating light in

that direction with the same intensity as sixteen standard candles. The brightness of a surface should therefore be as great when it is illuminated by the lamp as when it is illuminated by sixteen standard candles substituted for the lamp, whatever its distance from the lamp may be. But if the lamp is giving light of very different colour to the candles, this is no longer true, when the distance from the light source to the surface is very great. As these limiting cases are of no practical importance, we need not consider them further.

The second question, whether it is the brightness which we really want to measure, is of more importance. We do not produce illumination on a surface for the purpose of admiring its brightness; we produce it because we wish to see something on that surface. To take a concrete case, we illuminate the page of a book because we wish to read what is printed there. Now it does not follow that when we illuminate the page with red light we can read with as great ease as when we illuminate it equally brightly with green light. The ease with which we read depends upon the distinctness with which we can distinguish the printed letters, upon what is termed visual acuteness or distinctness of vision. Is it not desirable, therefore, that we should measure this property in a photometer, rather than brightness of illumination? The answer to this question appears to be a matter of taste, but one thing is clear. If we compare the two lights by comparing the brightness of illumination which they produce, we are measuring what definition and usage has stereotyped as their candle-power. If we compare them by comparing the distinctness with which they allow certain things, such, for example, as

printing, to be seen, we are measuring another property which should not be given the same name. It may be a very useful property to measure, but it is not the candle-power. It has been suggested to call this property the *visual intensity* of the light source to distinguish it from its luminous intensity. It may or may not have the same numerical value as the luminous intensity when expressed in terms of the same standard. When the tints of the lights from the two lamps, the test lamp and the standard, are the same, the visual and the luminous intensities will be equal, but when the tints are different, especially if they are greatly different, their values will not be precisely the same. Various photometers have been devised for measuring visual intensity; they are distinguished as *discrimination photometers* and depend on the principle of balancing the two lamps by obtaining a position in which a diagram or pattern of some sort on the photometer screen can be distinguished with equal ease on both surfaces. The principle on which these photometers depend shows up an inherent defect in this method of comparing lamps. Some standard pattern must be agreed upon as the pattern to be distinguished, as otherwise consistent results cannot be expected. In comparing the relative visual intensities of a red lamp and a green lamp, different results will obviously be obtained by using a black pattern on a white ground, and a red pattern on a white ground. This makes it clear that the visual intensity is not an inherent property of the light source, and any objections which can be brought against the comparison of different coloured lights on the basis of luminous intensity apply with far more force to the comparison on the basis of visual intensity. A lamp

has as many visual intensities as there are colours in the rainbow; its candle-power may be not quite determinate, but it is not so indefinite as this.

Some space has been devoted to the discussion of these points on account of the importance of heterochromatic photometry in the testing of modern lamps, the different types of which vary very greatly in the colour of the light they give. The white light of the Nernst lamp or metallic-filament lamp, the reddish-yellow light of the carbon-filament lamp, the intense yellow light of the flame arc, and the green light of the mercury-vapour lamp, have all to be compared by the present-day electrical engineer. From what has been said, it is clear that if the candle-power of any of these lamps is to be measured it should be measured by an ordinary photometer. A discrimination photometer may be used, because it is then easier to obtain balance; in such case the candle-power is not measured, but the value obtained may generally be called candle-power, because in most cases it will not differ from the true candle-power by more than the difference due to other errors of observation.

Heterochromatic Photometers.

In order to obviate the difficulties of heterochromatic photometry, the method of observing the photometer screen through a coloured glass may be used. This amounts practically to a somewhat crude use of spectrophotometry. Instead of comparing the total brightness of illumination, we compare the brightness for a particular colour. The value obtained for the candle-power by a single reading with glass of a particular colour is not, of course, the true

candle-power of the lamp, but only its candle-power for light of a special colour. It can, however, be shown that, if I is the candle-power of the lamp, G its candle-power for green light, and R its candle-power for red light, the two ratios $\frac{I}{R}$ and $\frac{G}{R}$ vary continuously. This rule only applies strictly when G and R are the candle-powers for light of certain definite wave-lengths. We can express it in the form

$$\frac{I}{R} = f\left(\frac{G}{R}\right),$$

or

$$I = f\left(\frac{G}{R}\right) R.$$

Now the value of the function $f\left(\frac{G}{R}\right)$ can be determined once and for all for the two glasses used for various values of $\frac{G}{R}$; and if c be the value thus found, we get

$$I = c\,R.$$

The way of using this method is then clear. The values of G and R are determined by measurement with the green and red glasses. $\frac{G}{R}$ is then known, and the corresponding value of c obtained from the previous determinations enables the value of I to be calculated. The table connecting c and $\frac{G}{R}$ will only apply to lamps giving light of approximately the same tint. Hence the method, though suitable when a large number of candle-power measurements have to be made for lamps of a particular type, is not very well adapted for general use. The method is known as Macé de Lepinay's method. A modification, due

to Crova, allows the candle-power to be determined by a single measurement. This depends upon the fact, true for lights of nearly the same tint, that the actual candle-power is proportional to the candle-power for light of wave-length 0·582 μ. A solution of perchloride of iron and chloride of nickel in certain proportions transmits waves of this length only, within very narrow limits, and a screen consisting of a cell containing this solution, or a glass of, as near as possible, the same colour, is employed to filter the light before it is observed. Photometers based on either of these methods do actually serve to measure the candle-power and not the visual intensity.

Discrimination photometers need not be described at any length. In all the characteristic feature is that a pattern of some form or other is drawn on the two illuminated surfaces in the photometer head. In the earlier work in this direction an ordinary printed page was employed. More recently the use of particular patterns drawn on the screen have been suggested, and several types of photometer heads have been designed in this way. The most recent and most carefully thought-out example is the discrimination photometer described by Prof. Fleming in his paper on photometry before the Institution of Electrical Engineers in 1902.[1] For reasons which have already been given, the author is of opinion that the use of this method of photometry is to be deprecated.

Flicker Photometer.—This form of photometer head depends on a principle different to that of either the ordinary photometers or the discrimination photometers.

[1] *Journal of the Institution of Electrical Engineers*, Vol. XXXII., p. 119.

It depends upon the fact that if the eye observes alternately in rapid succession two illuminated surfaces, a flickering sensation is noticed so long as the brightness of the two surfaces is not equal. The "flicker" disappears with considerable sharpness at the position of balance, even when the colour of the two lights is markedly different, and the position of balance is thus much easier to obtain than when the brightness is compared in the usual way. Once again the question is raised as to whether the comparison which is made with the flicker photometer is really a comparison of candle-power. In the writer's opinion, it is not. The flicker depends primarily on the phenomenon of persistence of vision. If the two illuminated surfaces are presented to the eye alternately with sufficient rapidity, no flicker is observed, however different their brightness. If, on the other hand, the alternations are sufficiently slow, there is always a flicker. Between certain fairly wide limits of speed, it is true, it is possible to obtain a position of balance, though there is a certain critical speed at which the accuracy is greatest. In spite of this, the fact that the disappearance of the flicker depends on the rapidity of the alternation seems to be sufficient evidence that the phenomenon observed differs essentially from the phenomenon of brightness. The flicker photometer further possesses the defect that it is apparently subject to the same colour defects as other photometers. Its only advantage lies in the fact that it is easier for an inexperienced person to compare lamps giving light of different tints by means of the flicker photometer than by means of an ordinary photometer. The results will also, in most cases, agree with those obtained by correct methods within the ordinary limits of

error. The argument in favour of the flicker photometer must be an argument based on its practical convenience in spite of its unscientific basis. For a full discussion of the properties of flicker photometers, the reader may be referred to a valuable paper by Mr. J. S. Dow on "The Theory of Flicker Photometers," in *The Electrician*,[1] and some correspondence in the same journal which followed it.

In the flicker photometer devised by Prof. Rood, the two illuminated surfaces of a wedge are viewed alternately through a lens which oscillates to and fro, so as to bring first one and then the other surface into view. In the Whitman type, one of the illuminated surfaces is rotated in front of the other, which is kept stationary. A section is cut out of the rotating surface, and thus the two surfaces are viewed alternately. Practically any form of ordinary photometer can obviously be converted into a flicker photometer in one or other of the two ways described above.

Illumination Photometers.

There have lately come into use a number of photometers which are distinguished by the name of illumination photometers, as they are designed to measure the illumination on a given surface, instead of the candle-power of the light-source. Such photometers are likely to prove of considerable value in the study of illumination, but this is a wider and somewhat different study to that of lamps. It has been pointed out already that a lamp is only a means to an end, the end being the production of illumination. The illumination depends, however, on a great many things

[1] *The Electrician*, Vol. LVIII., pp. 609 and 647.

besides the lamp used to produce it. The final test of good lighting is the test of whether the desired illumination is obtained, but this is not the test of a good lamp. Better illumination may be obtained from bad lamps well arranged than from good lamps badly arranged. This fact is becoming more and more recognised, and the use of illumination photometers is likely to increase in consequence. Nevertheless, the subject is somewhat outside the scope of this book, and we shall not do more than indicate the principle, which is an exceedingly simple one, on which these photometers are based. Suppose we have a room lighted by any number and variety of lamps, and it is desired to find the illumination on any surface, say a table, in the room. This can be found by measuring the candle-powers of all the lamps in the room in the direction of the surface, their distances from the surface and the angles between the normal to the surface and the incident rays, and calculating from these data the resultant illumination. All reflected light from ceiling and walls will have to be taken into account, and it is easy to see that such a calculation becomes an exceedingly complicated matter. The illumination can, however, be measured directly by an illumination photometer, by comparing the brightness of a given surface, say a white card, placed in the desired position, with the brightness of a similar card illuminated under conditions which allow its illumination in candle-feet to be directly calculated. A typical photometer for this purpose, which is based on designs by Mr. A. P. Trotter, has recently been described in *Electrical Engineering*.[1] The photometer (Fig. 12) consists of a closed box containing

[1] *Electrical Engineering*, Vol. I., p. 849.

a lamp L, the light from which, after reflection from a mirror M, falls on a screen S_1. This screen is viewed through slits in a second screen S_2 on the outside of the box. The angle of the screen S_1 can be adjusted until its apparent brightness is equal to that of S_2, which is illuminated by the general lighting in the street or room. A pointer attached to S_1 moves over a graduated scale, which allows the illumination to be read off directly in candle-feet for a given candle-power of the standard lamp L. This lamp is supplied with current by a small battery, and the whole apparatus is easily portable. The instrument is manufactured by Messrs. Everett, Edgcumbe & Co. A somewhat similar instrument has been devised by Mr. Haydn Harrison in which a flicker screen is used.

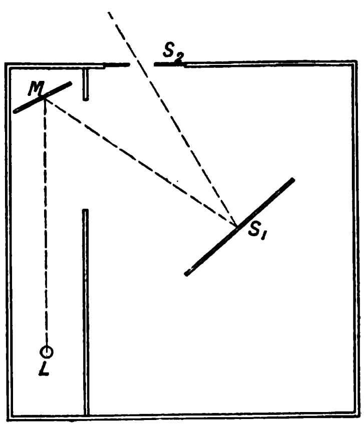


FIG. 12.—Everett-Edgcumbe Illumination Photometer.

These instruments can clearly also be used for the measurement of candle-power, and their employment in this way has been found convenient for some of the most modern types of electric lamps. For example, the mercury-vapour lamp, and still more, the Moore tube lamp, are extremely difficult to photometer in the ordinary way on account of the fact that, having light-sources of very large area, the inverse square of the distance law cannot be

applied. In order to determine the illuminating value of these lamps, recourse has been had to the following method. A given space, for example, a large room, is illuminated by one (or more) of these lamps, and the value of the illumination at different points is measured by means of an illumination photometer. The room is then illuminated by lamps, the candle-power of which can be determined in the usual way, and the illumination under these conditions is again measured. From the known candle-power of these lamps, the equivalent candle-power of the original lamp can then be calculated. This method is open to many grave objections, the chief of which is the difficulty, amounting almost to impossibility, of obtaining precisely the same distribution of the illumination under both conditions of test. It can only be regarded as an approximate method, but on account of its convenience in these special cases, is worthy of consideration.

Standards of Light.

All photometry involves the use of a standard lamp, with which the test lamp can be compared, and much experiment has been undertaken to evolve a satisfactory standard for this purpose. No attempt can be made here to discuss the various standards in detail. All the standards are arbitrary; there is no such thing at present as an absolute standard derived from the fundamental units of mass, length and time, though such a thing is conceivable and may one day be evolved. In the meantime, we must content ourselves with an arbitrary standard, the chief requirement of which is that it should be easily and accurately reproducible.

The standard English candle is a candle of certain composition and weight, burning at a defined rate. As a practical standard it is no longer used; its place has been taken by the Harcourt 10 candle-power pentane lamp. This lamp burns pure pentane and is of certain definite construction and dimensions. When burning under certain defined conditions it gives a light equivalent to that of ten standard candles. This lamp is the official standard of the Metropolitan Gas Referees and the National Physical Laboratory. Its candle-power varies appreciably with atmospheric conditions, and this fact, combined with a certain amount of difficulty in using it renders it a not very convenient standard except for very careful work. A careful investigation of this lamp was made by the National Physical Laboratory, and the results are embodied in a paper by Mr. C. C. Paterson, read before the Institution of Electrical Engineers in 1907.[1]

The Hefner lamp is the official German standard of light. It is a lamp of extremely simple construction, burning amyl-acetate. The lamp must be used under certain specified conditions to give its correct candle-power.

The Carcel lamp is the French standard. Like the other standards, it is a lamp of specified construction and must be burnt under certain specified conditions; the fuel is colza oil.

The simplest and most convenient of these three standards is the Hefner lamp, and this has led to the proposal that it should be adopted as an universal standard.

[1] *Journal of the Institution of Electrical Engineers*, Vol. XXXVIII., p. 271.

As has already been pointed out, this need not involve any alteration in the value of the standard English candle any more than the use of the Clark cell involves the necessity of altering the value of the volt, though, on the grounds of uniformity, such an alteration is desirable in the case of the candle. All three lamps possess the disadvantage that inaccuracies in construction, atmospheric conditions and errors in adjustment in use alter the values of their candle-power. An attempt to overcome these difficulties has been made by the endeavour to use some more definitely reproducible phenomenon as a standard. The Violle unit, sometimes incorrectly called an absolute unit, makes use of the light given by molten platinum at its melting-point as the standard. The unit is the light from one square centimetre of pure platinum at its melting-point. It is approximately twenty candles. A very large amount of work has been done in the endeavour to make this unit one of practical utility, but at present very little success has been attained. The relative values of the candle, the hefner, and the carcel were thoroughly investigated recently by the National Physical Laboratory in England, the Reichanstalt in Germany and the Laboratoire Centrale and Laboratoire d'Essais in France. The results are given in the paper by Mr. C. C. Paterson, to which reference has already been made. The following table shows the values obtained in terms of the English candle (Pentane standard), and incidentally illustrates the agreement obtainable under present conditions with photometry at different times and places and by different people working under the most accurate conditions possible :—

TABLE IV.

	Candle.	Hefner.	Carcel.
National Physical Laboratory	1	0·914	0·982
Reichanstalt	1	0·917	0·991
Laboratoire Centrale . .	1	0·929	1·000
Laboratoire d'Essais . .	1	0·928	0·996

Since the date of Mr. Paterson's paper a meeting of the International Photometric Commission has been held (at Zurich, in July, 1907), at which the values given in Table V. were unanimously adopted for the ratios of the different units. These values differ slightly from the mean of the values given in Table IV., owing to the results of other observations and corrections being included in their determination. It is stated that they may be regarded as correct within the limits of plus or minus 1 per cent.[1]

TABLE V.

	Candle.	Hefner	Carcel.
Candle	1·0	1·095	1·02
Hefner	0·915	1·0	0·93
Carcel	0·98	1·07	1·0

The value of the candle in terms of the Hefner unit, hitherto generally accepted, is 0·88, which is 4 per cent. too small. The figures in Table IV. show that the Pentane and the Hefner lamps are distinctly preferable to the Carcel lamp for accuracy of reproduction.

[1] For a full report of the resolutions of the Commission, see *The Electrician*, Vol. LX., p. 6 (October 18th, 1907).

Secondary Standards.

The electrical engineer will probably not care to be troubled by using any of the primary standards of light. This is particularly the case as the standards are all flame standards and so come outside the range of his special knowledge and experience. In their place secondary standards may be used. Any source of light may be used as a secondary standard, but the most general is the carbon-filament incandescent lamp. The use of these standards for practical work has many advantages. A supply of current is always available when electric lamps are being tested, and this can be controlled and measured with great accuracy. A lamp can, moreover, be chosen which is nearly the same in candle-power as the lamp under test, and which gives light of the same colour. There is no reason why metallic-filament lamps should not be always compared with metallic-filament standards, Nernst lamps with Nernst standards, and so forth. These newer lamps have, however, been so short a time before the public, that there is hardly sufficient confidence in them as yet to enable them to be used as standards. Nevertheless, where colour difficulties are marked, this procedure will often greatly accelerate testing. In using electric lamps as secondary standards a reference standard should be employed which is carefully standardised against the primary Pentane (or Hefner) lamp, either by the observer himself, or better, officially at the National Physical Laboratory. From these any number of working lamps can be standardised, and these only used during the actual testing. The working standards must be verified as often as necessary against the

reference standards, and these in turn verified occasionally against the primary standard. It is always possible under these conditions to use for testing a lamp of the same candle-power, voltage, and type as the lamps being tested. Certain precautions must be taken which will become obvious when the peculiarities of the different types of lamp are considered. A very useful form of secondary standard incandescent lamp has been devised by Prof. Fleming, which will be described in the chapter on carbon-filament lamps, when the reasons governing its design will be better appreciated.

It has been impossible, in the necessary limits of this chapter, to investigate fully all the difficulties and sources of error in photometry, and the attempt has only been made therefore to discuss the more important principles and aspects of the subject. Photometry is of as great importance to the lamp maker and lamp user as electrical measurements of other kinds are to the electrical engineer, and it is only by a proper understanding of its fundamental principles and difficulties, and a discriminating use of the facilities it affords, that the production of artificial illumination can be converted from an art into a science.

CHAPTER IV

METHODS OF TESTING

THE testing of electric lamps divides itself naturally under two heads. Under the first, which may be called general testing, are included all the determinations of the physical properties and characteristics of the lamps. The precise tests which it is desirable to make of this kind vary with the type of lamp to be tested. Thus with arc lamps it is necessary to test the mechanical properties of the lamp, such as the certainty and precision with which the regulating mechanism operates; with Nernst lamps the time taken by the lamp to light up, the proportion of power absorbed in the steadying resistance, the perfection with which this resistance regulates the current, and other similar points should be tested. The consideration of tests such as these will be left until the different types of lamps are separately described. In addition, there are certain general tests which hardly come within the province of ordinary lamp testing; such are the characteristics of the lamp under varying conditions of use, the variation of current with voltage, of candle-power and of resistance with current and voltage, and so forth. The laws governing these variations may be studied separately for each type of lamp, but there is rarely any necessity for verifying them in the case of individual examples of each type.

These laws will also be considered under the headings of the various types of lamps.

The two most important general tests to make on a lamp are the test of the *distribution of the light* given by the lamp, and the test of what is generally known as the *efficiency* of the lamp, and with these we shall deal somewhat fully in this chapter.

The second division of lamp testing is that generally known as life-testing. It comprises the testing of the durability of the lamp, and the laws governing the variation of its usefulness as a light-source with the number of hours during which it has been used. This is naturally one of the most important tests to which a lamp can be subjected, and an attempt will be made in the present chapter to lay down the general rules under which such tests should be carried out. Life-testing is generally only applicable to incandescent lamps, but a somewhat similar test can be carried out on the carbons used in arc lamps, which will be dealt with in the chapter on arc-lamp carbons.

Distribution of Light.

The importance of knowing the distribution of light, or the candle-power of a given lamp in all directions radiating from the lamp as centre, cannot be over-estimated. Without this knowledge, it is impossible to say which is the most suitable lamp for a given purpose or what is the best way of utilising a particular lamp to obtain a desired end. An incandescent point light-source radiating with equal intensity in all directions, which is a convenient conception for deducing the laws of photometry, does not exist in

actual practice, all lamps departing more or less from this ideal conception. The distribution is further modified by the use of shades and globes, and the full study of this subject is consequently very complicated. The great advantages to be derived from the application of scientific principles to the design of shades and globes is well illustrated by the remarkably good results attained with holophane globes. In general, it is impossible to determine the light distribution of a given lamp, combined with all the different types of shade or globe with which it may be used, though it is desirable to know it for the more commonly occurring types and, if an installation of any size is to be put in using a particular type, the distribution should be determined for this combination. It is sufficient, therefore, in most cases to test the distribution for the lamp as it comes from the manufacturer, which may be looked upon as an unit. Even this is not a simple matter with the great variety of lamps now on the market. Thus with carbon-filament lamps alone, we have to consider lamps with filaments of all possible forms and with bulbs of a very great variety of shapes, which may be partly or wholly frosted or partly silvered. With arc lamps the lamp itself forms part of the necessary lighting unit, and the distribution with different makes of lamp should be determined, as such points as the shape and size of the globe, the relative position of the arc, and the size and nature of the under-surface of the lamp above the arc may materially affect the distribution of light with an arc of given length and power between carbons of given quality and size.

It will readily be seen that it would be impossible to deal with all the conditions likely to be met in practice in this

or any book. The engineer should, therefore, be in a position to determine these points himself, or the manufacturer should be prepared to supply, as has been suggested by Prof. Fleming, curves showing the distribution with his particular make of lamp, the accuracy of which he should be required to guarantee.

If the candle-power of a lamp be measured in all direc-

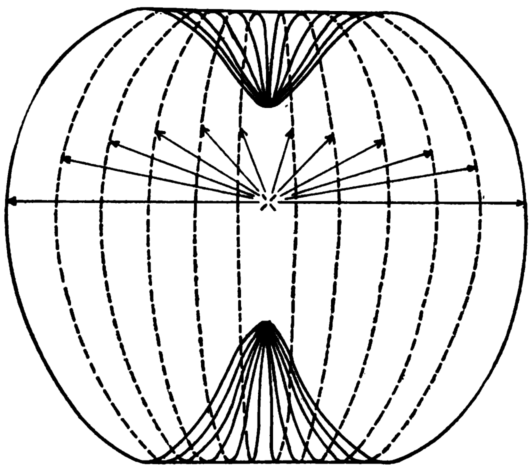


FIG. 13.—Half photometric surface.

tions radiating from the light-source as centre, and if for each direction a radius be drawn from this centre proportional in length to the candle-power, the ends of all these radii lie on a surface which is called the *photometric surface* for the lamp. The half of such a surface is shown in Fig. 13. A full determination of the light distribution for a given lamp involves the determination of the form of this surface, but this would not only be an extremely laborious

operation, but would give a result very difficult to represent graphically and practically necessitating the use of solid models. In general, the problem may be much simplified by determining the distribution in certain planes passing through the source, namely, the horizontal plane and one or more vertical planes. These planes should all meet in one point in the lamp, which may be called the optical centre of the lamp. The precise position of this point is difficult to define. It should be symmetrically placed with regard to the actual light-giving source, the filament or arc. It is generally possible to imagine one horizontal plane and two vertical planes at right angles passing through the light-source, as shown in Fig. 14, in such a way that the amount of light-giving surface on one side of any of these planes is equal to the amount on the opposite side; the intersection of these planes will be the point required. In determining the light distribution all measurements start from this point. The lamp must, therefore, be mounted so that this point (or its image, if mirrors have to be used between the light-source and the photometer head) lies in the horizontal line passing through the centre of the photometer screen and parallel to the axis of the photometer

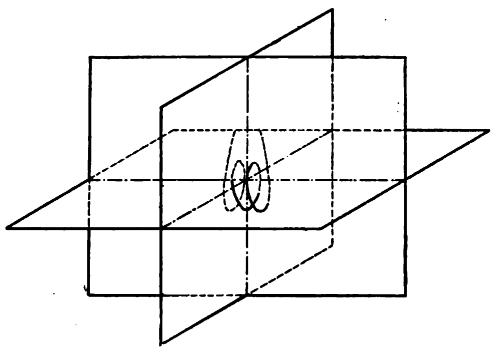


FIG. 14.—Determination of optical centre of lamp.

bench; and so that the distance of this point from the photometer screen can be accurately determined. This is, of course, usually effected simply by correctly centring the lamp on its carriage.

Horizontal Distribution.

The lamp having been mounted vertically, the distribu-

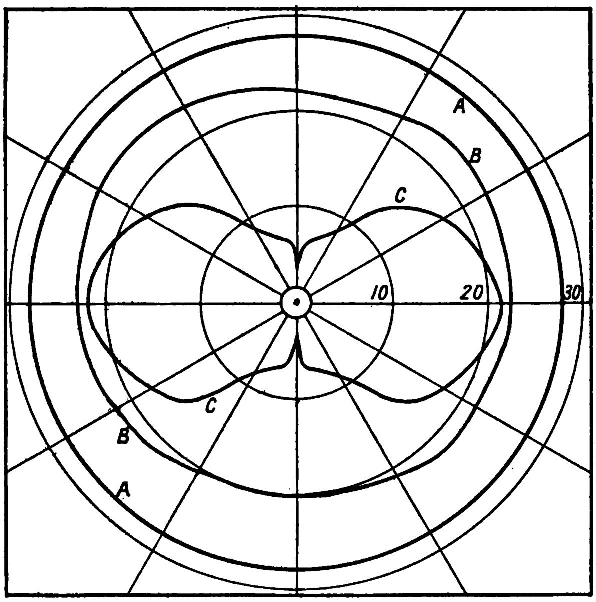


Fig. 15.—Horizontal distribution curves.
A, Tantalum lamp. *B*, Carbon-filament lamp. *C*, Nernst lamp.

tion of light in the horizontal plane can be determined by measuring the candle-power in a given direction, then rotating the lamp around the vertical axis through a certain angle, and again measuring the candle-power,

repeating this operation until the lamp has been rotated through 360°. Measurements may be made every 5°, 10°, or 20°, according to the accuracy it is desired to obtain. In nearly all cases, the determination of the horizontal distribution offers practically no difficulty, as almost all types of lamp can be hung vertically and rotated around the vertical axis with ease.

The results obtained may be plotted as a polar diagram in the usual way. The radius vector in a given direction is made proportional in length to the corresponding candle-power, and the ends of all these lines are joined up by a curve. This curve is the horizontal section of the photometric surface. On the same diagram should also be shown the projection of the light-source on the horizontal, so that the relation between the diagram and the lamp is clear. In Fig. 15 are shown three such diagrams. The curve A is for a tantalum lamp, B is for a carbon-filament lamp, and C for a Nernst lamp with straight horizontal filament. It will be seen that the horizontal distribution with the tantalum lamp is uniform, the curve being, in this case, a true circle; with the carbon-filament lamp the curve is somewhat less regular, and with the Nernst lamp is butterfly-shaped. The horizontal distribution with the carbon filament is nearly uniform, but with the Nernst filament it is very far from uniform. The mean horizontal candle-power (M.H.C.P.) of the lamp can be obtained accurately from these curves. It is, as already defined, the mean value of the horizontal intensity in all directions. If I_m be the mean horizontal candle-power, and $i_1, i_2, i_3, \ldots i_n$ the horizontal candle-power at equal angular intervals,

$$I_m = \frac{i_1 + i_2 + i_3 + \ldots + i_n}{n}$$
$$= \frac{i_1\,d\theta + i_2\,d\theta + i_3\,d\theta + \ldots + i_n\,d\theta}{n\,d\theta}$$
$$= \frac{\int_0^{2\pi} i\,d\theta}{2\pi}.$$

Now if a second polar curve be drawn such that its

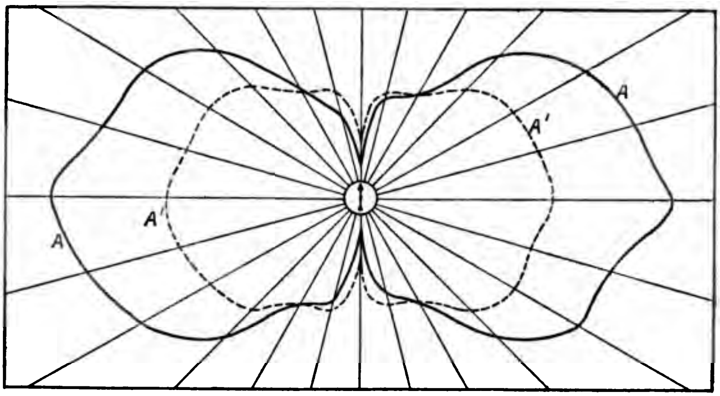


FIG. 16.—Graphical determination of mean horizontal candle-power.
A, Horizontal distribution curve. *A'*, Secondary curve.

radii are equal to the square roots of the radii of the distribution curve, that is to say, such that

$$i' = \sqrt{i}$$

we have

$$I_m = \frac{\int_0^{2\pi} i\,d\theta}{2\pi}$$
$$= \frac{\frac{1}{2}\int_0^{2\pi} i'^2\,d\theta}{\pi}$$
$$= \frac{1}{\pi}\text{ (area of new curve).}$$

In Fig. 16 are shown the horizontal distribution curve A for a Nernst lamp and the secondary curve A′, the radii of which are proportional to the square roots of the corresponding radii of the curve A. For the sake of clearness, the scale for the secondary curve has been made four times that for the primary curve. It is important to notice that it is the area of this secondary curve and not

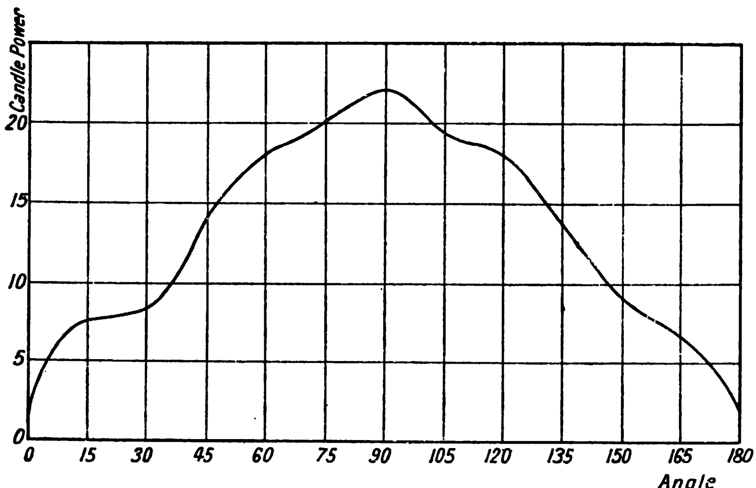


FIG. 17.—Horizontal distribution curve to rectangular co-ordinates.

the area of the distribution curve which is proportional to the M.H.C.P. The area of the secondary curve can be measured in the usual way by a planimeter.

A simpler graphical method is to plot the distribution curve to rectangular co-ordinates, as in Fig. 17, which shows the horizontal distribution of the light for the same lamp as Fig. 16. The mean height of this curve gives the mean horizontal candle-power of the lamp, and

this is found by dividing the area of the curve by its base.

In practice, however, it is generally not necessary to use either of these graphical methods unless great accuracy is required or the curve is very far from symmetrical. It is usually sufficient to find the value of the horizontal intensity in a fair number of directions and take the arithmetical mean of the results obtained. The number of measurements made must depend on the accuracy desired and the degree to which the curve is symmetrical. Thus, for curve A (Fig. 15) a very few measurements would suffice; for curve B the number would have to be rather greater, and for curve C (which is practically the same as the curves in Figs. 16 and 17), a considerable number would be needed. On account of the very low values of the candle-power for this curve (C) in the directions 0° and 180°, undue weight is given to these values if they are included in the results used for obtaining the value of the M.H.C.P. This is well illustrated by the figures in Table VI.

TABLE VI.

MEAN HORIZONTAL CANDLE-POWER FOR NERNST LAMP (FIGS. 16 AND 17).

From area of secondary curve in Fig. 16	13·4
From area of curve in Fig. 17	13·5
From 25 measurements	12·7
From 23 measurements (excluding those at 0° and 180°)	13·6
From 13 measurements	12·5
From 11 measurements (excluding those at 0° and 180°)	14·0
From 7 measurements	11·2
From 5 measurements	9·9

The mean horizontal candle-power may be more quickly determined in other ways. For lamps of a given type with

filaments of a certain shape, the distribution curves will all be similar. The mean horizontal candle-power will therefore bear a definite relation to the candle-power measured in any one special direction. The value of this ratio can be determined once and for all for the particular type of lamp, and the value of the M.H.C.P. can then be obtained from a single measurement. For example, the horizontal candle-power in the plane of the filament, or in a plane at right angles to this, can be measured; or in a plane making an angle of 45° with that of the filament. Measurements of this sort are, however, only approximate being liable to error from two causes. The lamp may not have, for one reason or another, precisely the same distribution curve as the type, and the candle-power measured may not be in precisely the correct vertical plane. On account of this second cause of error, the position chosen should be one at which the candle-power is approximately constant throughout a small angle on either side of the correct direction, and that this is true of the particular lamp under test should be verified in each instance. A second quick method of determining the M.H.C.P., and one very commonly used, is to mount the lamp on a stand, which can be rotated around the vertical axis at a speed of from 200—400 revolutions per minute.[1] Owing to persistence of vision the illumination on the photometer screen then appears constant and the value of the M.H.C.P. is thus obtained at a single reading. The horizontal distribution can be determined for the type of lamp as before. This method is in very general use, especially in America. An

[1] 200 revolutions per minute is the speed specified in the Engineering Standards Committee specification for carbon-filament glow lamps.

objection to this method, apart from the complications due to sliding contacts, is that the filament may be slightly distorted in shape by the rotation, but recent experiments by Messrs. Hyde and Cady at the Bureau of Standards show that the error from this cause, unless the speed is so high that the filament is forced against the bulb, does not exceed 1·5 per cent.

In a valuable paper[1] by Mr. A. Russell is given the distribution curve for a carbon-filament lamp determined with great care. The curve is very far from being a smooth curve, the irregularities being due, Mr. Russell pointed out, to the reflecting action of the part of the bulb behind the filament, which causes a great and very sudden increase of candle-power in certain directions, and to the partial obscuring of one part of the filament by another, which causes a sharp drop of candle-power in other directions. The curve illustrates clearly, in the same way as does the Nernst lamp curve already considered, the necessity of precautions being taken when making measurements of M.H.C.P., especially when this value is deduced from a single measurement.

VERTICAL DISTRIBUTION.

Having determined the horizontal distribution, it is necessary to determine the distribution of light in one or more vertical planes. The number of planes in which this is done depends on the shape of the horizontal distribution curve. When the distribution is symmetrical about the vertical axis, in which case the light-source is said to be

[1] *Journal of the Institution of Electrical Engineers*, Vol. XXXII., p. 633, 1903.

axially symmetrical, it is sufficient to determine the vertical distribution in any one vertical plane. Many lamps practically satisfy this condition, as, for example, the tantalum lamp A or the carbon-filament lamp B in Fig. 15, a Nernst lamp with straight vertical filament, or an ordinary open type arc with properly centred carbons. In such a case the vertical distribution curve, if rotated about the vertical axis, sweeps out the photometric surface. Many lamps, however, do not satisfy this condition even approximately. For example, the Nernst lamps in Figs. 15 and 16 are very far from being axially symmetrical.

In general, in such cases, it is sufficient to determine the vertical distribution in two planes at right angles, one of which is the plane of the filament. The determination of the vertical distribution curve is somewhat more difficult than that of the horizontal curve. If the lamp can be burnt in a horizontal position, then it can be mounted horizontally and the curve obtained by rotating the lamp in exactly the same way as the horizontal curve is obtained.

With large lamps it is often not possible to adopt this method, and some lamps will not burn correctly in this position, as for example arc lamps. In such cases the photometer bench and comparison lamp may be mounted on a frame, so that they can be turned to point towards the lamp under test in the desired directions: this is not, however, a convenient arrangement and recourse is generally had to the use of mirrors so arranged that the light radiated at any given angle can be caught and reflected horizontally along the photometer bench. A correction must be made for the loss by reflection, and in order that a constant value for this correction may be obtained the light

must always fall on the mirror at the same angle. This can be ensured by arranging each mirror so that when it is turned to catch the light coming in different directions it is rotated about an axis making an angle of 45° with its plane. One method of arranging this is shown in Fig. 18. The figure shows the apparatus in perspective elevation and in plan. The lamp is suspended at L, so that it can be raised or lowered; the light radiated in the direction L M falls on the mirror M and is reflected along M P to the photometer screen. As the lamp is raised or lowered the mirror is rotated about the axis M b to catch the light coming at different angles. This arrangement has the disadvantage that the distance of the lamp from the mirror M varies with the height of the lamp. This may be avoided by using the arrangement shown in Fig. 19, in which three mirrors are used mounted on a frame rotating about the axis x y. The distance the light travels before arriving at the last mirror is constant. Other arrangements can be easily devised.

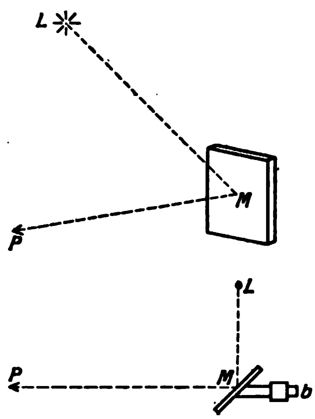


FIG. 18. — Determination of vertical distribution curve.

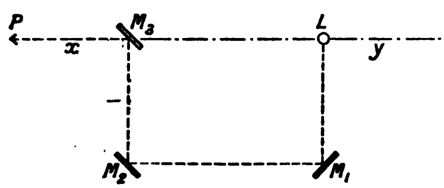


FIG. 19.—Determination of vertical distribution curve.

The number of measurements which it is necessary to make must be determined, as with the measurement of horizontal distribution, by the accuracy desired. For reasons which will be made clear in the next section the measurements near the horizontal are more important than those near the vertical.

MEAN SPHERICAL CANDLE-POWER.

From the vertical distribution curve the value of the mean spherical candle-power can be obtained graphically. Several methods have been suggested, but the simplest and most generally used is that due to Rousseau. All these methods assume that the source of light is symmetrical about the vertical axis, and that, therefore, the revolution of the polar vertical distribution curve about its vertical axis sweeps out the photometric surface. In Fig. 20 let A B C represent the vertical distribution curve for a lamp at O, supposed axially symmetrical. With O as centre and radius r, describe a circle A′ B′ C′ and draw a line P′ Q′ parallel to the vertical diameter P O Q. Let O A and O B be two radii of the distribution curve very close together, such that

$$\mathrm{O\,A} = \mathrm{O\,B} = i$$

the candle-power in the direction O A.

Now the luminous flux falling on a small element of the sphere A′ B′ C′ at A′ is equal to

$$i\, d\,\omega = i\,\frac{d\,\mathrm{S}}{r^2}$$

where $d\,\mathrm{S}$ is the area of this element. Since the value of i is by assumption constant for all rays making an angle P O A with the vertical, the luminous flux on the zone

of the sphere swept out by the revolution of A′ B′ around the axis P Q is

$$i \times \frac{\text{area of this zone}}{r^2}.$$

Now the area of this zone is $2 \pi r A_2 B_2$, where $A_2 B_2$ is the projection of A′ B′ on P Q. Hence the luminous flux on this zone is

$$\frac{i \times 2 \pi r A_2 B_2}{r^2} = \frac{2 \pi}{r} A_2 B_2 . i.$$

If from A′ and B′ perpendiculars be drawn to P′ Q′, meeting

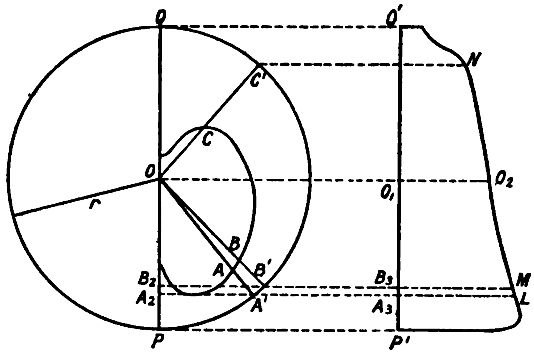


FIG. 20.—Graphical construction for mean spherical candle-power (Rousseau's method).

it in A_3 and B_3, and produced so that A_3 L is equal to O A and B_3 M to O B, we have

$$\text{flux on zone swept out by A′ B′} = \frac{2 \pi}{r} . A_2 B_2 . i$$

$$= \frac{2 \pi}{r} A_3 B_3 . i$$

$$= \frac{2 \pi}{r} \times \text{area } A_3 \text{ L M } B_3.$$

If a similar construction is made for all the other radii of the distribution curve, we obtain the *Rousseau figure* P′ L M N Q′, such that

Luminous flux on sphere A′ B′ C′ $= \frac{2\pi}{r} \times$ area of P′ L M N Q′, or the total luminous flux from the source is equal to $\frac{2\pi}{r} \times$ area P′ L M N Q′.

If a source of light giving the same luminous flux as the actual source but of uniform intensity I be substituted for it the total luminous flux from this source is $4\pi I$ (see p. 30); but I is by definition the mean spherical candle-power of the actual source, and we have

$$4\pi I = \frac{2\pi}{r} \times \text{area } P' L M N Q'$$

$$\therefore I = \frac{1}{2r} \times \text{area } P' L M N Q'$$

$$\text{or } I = \frac{\text{area } P' L M N Q'}{P' Q'}.$$

The area of the Rousseau figure can be measured by means of a planimeter and the mean spherical candle-power directly calculated from it. The mean hemispherical candle-power of both the upper and lower hemispheres may be obtained in the same way by measuring the areas $P' O_1 O_2 M P'$, and $Q' O_1 O_2 N Q'$.

When the source of light is not axially symmetric there are several ways in which an approximation to the mean spherical candle-power can be obtained. The vertical distribution curves in two or more vertical planes can be drawn and the M.S.C.P. determined in the above manner for each, the mean of the results being taken as the correct value. A simpler method, when the horizontal distribution

is nearly symmetrical, is to determine the vertical distribution in one plane only and from this to calculate the mean spherical candle-power. If i be the value of the horizontal candle-power in this plane and i_m the value of the mean horizontal candle-power, such that $i_m = k\,i$, it may be assumed that approximately

$$I_m = k\,I,$$

where I is the mean spherical candle-power as found and I_m the true mean spherical candle-power.

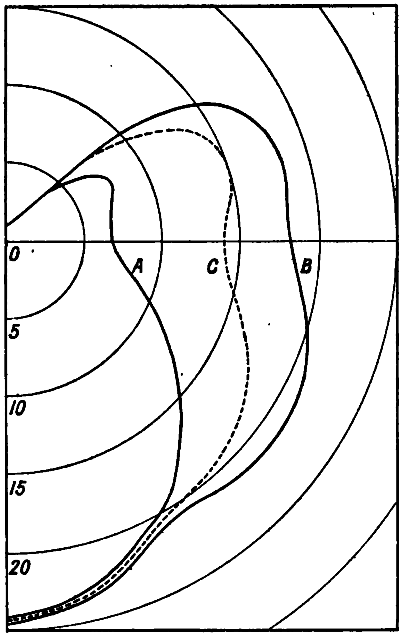


FIG. 21.—Mean vertical distribution curve for unsymmetrical lamp.

If the horizontal distribution is far from uniform, the following method, suggested by the writer[1] may be used and gives very accurate results. The distribution in the horizontal plane and in two vertical planes at right angles is measured. In Fig. 21 are shown the two vertical distribution curves A and B for a Nernst lamp with straight horizontal filament. The horizontal curve for this lamp, as may be seen from the similar curve in Fig. 16, can be obviously divided into four similar quadrants, and only one

[1] *The Electrician*, Vol. LVI., p. 91, 1905.

such quadrant need be considered, the values for the candle-power taken at the various angles being the means of the actual values found in the four quadrants. These values are plotted to rectangular co-ordinates as the curve, 90°, in Fig. 22. The mean height of this curve gives the mean

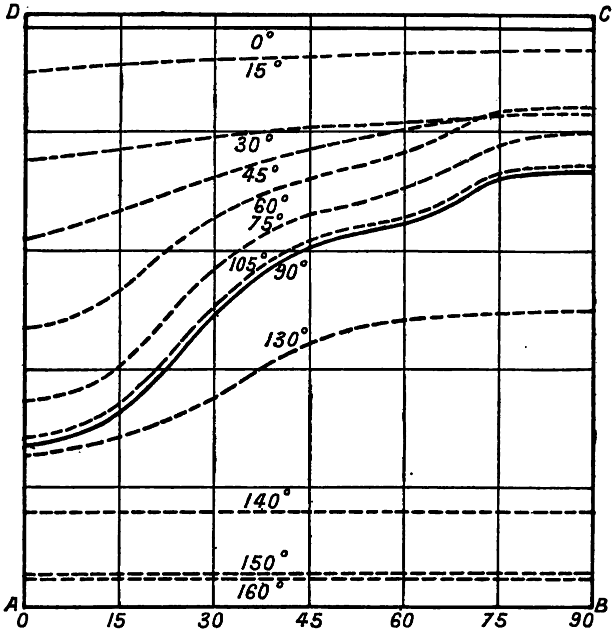


Fig. 22.—Determination of mean vertical distribution curve.

horizontal candle-power. Consider now the distribution of light below the horizontal. If a sphere be described around the source of light and be divided into a number of horizontal zones, we can obtain the M.S.C.P. from the Rousseau figure if we know the mean intensity of the flux on each zone. The problem then is to find the mean

candle-power along the surface of a cone of given vertical angle, and to obtain this we have to obtain the distribution of light for this cone. The distribution of light for a cone having a vertical angle of 0°, *i.e.*, in a direction vertically downwards, is obviously a circle, and hence is represented in Fig. 22 as a straight line (0°, Fig. 22). Both the curves 0° and 90° may be regarded as having been experimentally determined, and are therefore both drawn in full in Fig. 22. As we pass from the horizontal zone to the vertical the curve of distribution for the zone must obviously change gradually in shape from curve 90° to curve 0°. The starting and finishing points of all the curves for the different zones are already known, having been determined in the measurements of vertical distribution for curves A and B (Fig. 21). The values found in the plane of the filament are plotted on A D, and those in the plane at right angles to the filament on B C. and these points are then joined by a series of curves merging gradually from the shape of curve 90° to that of curve 0°. The curves for angles 15°, 30°, 45°, 60°, and 75° are shown in the figure. In a similar way the curves for 105°, 130°, 140°, 150°, and 160° are obtained. By measuring the area of any one of these curves the value of the mean candle-power for this zone is obtained. These values are now plotted as a mean vertical distribution curve, C, Fig. 21, which represents the vertical distribution for an axially symmetrical source of light, having the same M.S.C.P. as the actual source. This curve may now be used to obtain the Rousseau figure and the M.S.C.P. found as already described.

The graphical determination of the mean spherical

candle-power is a somewhat lengthy process and involves the use of a planimeter, which is an instrument rarely in the possession of the electrical engineer.[1] This difficulty may be overcome by adopting a method suggested by Mr. A. Russell in the paper to which reference has been made above. Instead of measuring the candle-power at equal angular intervals, the measurements are made at certain definite angles determined in the following way. Let O P, Fig. 23, be the vertical axis through the source of light, and let it be divided into any number of equal parts, O A_1, A_1 A_2, A_2 A_3, A_3 P. From the centre points of each of these parts horizontal lines are drawn meeting the circumference of the circle with O as centre and radius O P in P_1, P_2, P_3, P_4. The candle-power is then measured in the directions O P_1, O P_2, O P_3. It is clear that

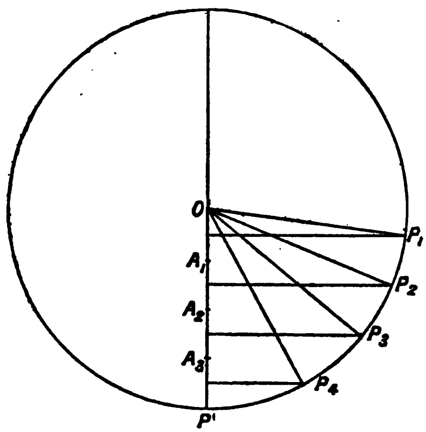


FIG. 23.—Determination of mean spherical candle-power.

[1] Since the above was written a new graphical method of determining the mean spherical candle-power which does not involve the use of the planimeter, has been published by Dr. Kennelly (*The Electrical World*, Vol. LI., p. 645, March 28, 1908). The method leads to the M.S.C.P. being obtained as a straight line, the length of which can be measured; apart from the advantage of avoiding the necessity for a planimeter, Dr. Kennelly shows that the accuracy is slightly greater than that obtained with the Rousseau figure.

the zones of the sphere illuminated by $O P_1$, $O P_2$, $O P_3$, etc., have all the same area, namely, $2 \pi r h$, where $h = O A_1 = A_1 A_2$, etc. Hence the flux of light falling on the sphere is

$$\frac{2 \pi h}{r} (i_1 + i_2 + \ldots + i_n),$$

and the mean spherical candle-power is

$$\mathrm{I} = \frac{2 \pi h (i_1 + i_2 + \ldots + i_n)}{4 \pi r}$$

$$= \frac{h}{2 r} (i_1 + i_2 + \ldots + i_n)$$

$$= \frac{1}{n} (i_1 + i_2 + \ldots + i_n)$$

The M.S.C.P. is thus found without any graphical construction at all by measuring the candle-power at certain predetermined angles. The values of these angles for various numbers of measurements are given in Table VII.,

TABLE VII.

Number of Measurements.	Angle above or below horizontal.
2	30.
4	14·5, 48·6.
6	9·6, 30, 56·4.
8	7·2, 22, 38·7, 61.
10	5·7, 17·5, 30, 44·4, 64·2.
20	2·9, 8·6, 14·5, 20·5, 26·7, 33·4, 40·5, 48·6, 58·2, 71·2.

taken from Mr. Russell's paper. The mean of ten observations at the angles given in the fifth line of this table is, according to Mr. Russell, sufficiently accurate for all practical purposes. Of course the same corrections must be

applied as before when the light-source is not axially symmetrical.

This method brings out clearly the fact that the candle-power measurements at different inclinations to the horizontal vary greatly in importance. Whereas the area of a zone of the sphere of width s, illuminated by light radiated in the horizontal plane, is $2 \pi r s$, that of a zone of equal width, illuminated by light radiated at an angle θ with the horizontal, is $2 \pi r s \cos \theta$, and when θ is $90°$ this area is zero. The candle-power in the horizontal plane is therefore of the greatest importance, that in a direction vertically downwards or upwards of least. It is easy by the use of suitable reflectors or globes to very greatly increase the candle-power in the downward direction, and the high values of candle-power thus obtained create the impression that the lamp is giving a great deal of light. This, it is clear from the above, is incorrect. It is clear, also, that it is advisable, when measuring the vertical distribution, even when the M.S.C.P. is to be determined graphically, to make the measurements not at equal angular intervals but at the angles given in Table VII., as thus equal importance is given to each measurement, and more values are obtained near the horizontal, where the light is of value, than near the vertical, where it is comparatively useless.

The method already suggested for determining mean horizontal candle-power by finding the ratio between the M.H.C.P. and the horizontal candle-power in a certain direction for the type of lamp under test may be also applied to the determination of mean spherical candle-power. The factor by which the M.H.C.P. must be multiplied in order to obtain the M.S.C.P. is known as the spherical reduction

factor. It is generally in the neighbourhood of 0·8. A similar factor can be found for obtaining the M.S.C.P. from a single measurement, or from two or three measurements at certain angles.

A method for measuring the M.S.C.P. by a single photometric measurement has been recently perfected by Ulbricht and Bloch.[1] A hollow sphere, about 1 meter diameter, is constructed and whitened on the inside. The lamp to be tested is placed with its optical centre at the centre of this sphere. It can be shown that the illumination on any portion of the surface of this sphere, which is screened from the direct rays from the lamp, is proportional to the M.S.C.P. of the source, whatever the distribution of light. This illumination is measured by a suitable photometer at a peep-hole 50 *m/m* diameter in the sphere, an opaque screen 55 *m/m* diameter being fixed between this portion of the surface of the sphere and the light-source. The constant for the sphere can be determined by means of a lamp of known M.S.C.P. If the lamp is fixed with the light-source at the surface of the sphere, the measurement gives the M.H.S.C.P., but this is only true when the source is axially symmetrical. Small errors in centering are negligible when the M.S.C.P. is being measured, but somewhat more important in measurements of M.H.S.C.P.

Efficiency.

Having determined the M.H.C.P. and the M.S.C.P. of a lamp, it is possible to give figures for its efficiency as a light-source. The word "efficiency" has been more abused than any other in connection with electric lamps. The

[1] *The Electrician*, Vol. LVI., p. 1057, 1906.

word should properly only be used to express a numerical ratio between two quantities of the same kind. Thus it is correct to speak of the *luminous efficiency* of a light-source to express the ratio of the energy radiated as visible radiations to the total energy radiated, and in this sense we have already had occasion to use the word. These quantities are, however, hard to measure, and some much more simple criterion of the relative merits of different lamps is required. It is usual to obtain this from the ratio of the watts supplied to the lamp to the candle-power given by it. This ratio, *watts per candle-power*, is generally called the *efficiency* of the lamp ; as a matter of fact, even if the jumble of quantities be excused, it is not a measure of the efficiency but of the inefficiency, becoming obviously greater the less efficient the lamp. Further confusion is caused by the general omission to state whether the value taken for the candle-power is that of the maximum horizontal candle-power, the mean horizontal candle-power, or the mean spherical candle-power. It is doubtful whether any efforts will succeed in eradicating this inaccurate use of the word "efficiency," so strong a hold has it taken in our literature. Mr. Swinburne, in a recent paper before the Institution of Electrical Engineers, uses "efficiency" for the ratio of candles to watts, a somewhat more scientific proceeding and one having the advantage that high efficiency then corresponds with high numerical values of the ratio. But, unfortunately, the figures thus obtained are unfamiliar, and most engineers have to pass through the mental process of obtaining their inverse values before they have any clear idea of what they signify. We shall, therefore, in this book continue to compare lamps on the basis of their consumption in watts

per candle, but shall avoid the use of the word "efficiency" as a name for this ratio.

Lamps should always be compared on the basis of their mean spherical candle-power, as this is the only quantity which bears any definite relation to the amount of light they give. No juggling with globes or reflectors can increase the value of the mean spherical candle-power, whereas the mean horizontal candle-power or the mean hemispherical candle-power can be easily increased by this means. Comparison of lamps of the same type having the same distribution curves may be made on the basis of M.H.C.P., or any other candle-power, but the values are useless for comparison with lamps of another type having different distribution curves. These considerations have become of greatly increased importance now that there are so many different types of electric lamps on the market. It is often urged that the mean lower hemispherical candle-power is the most useful basis for comparison, especially for arc lamps used for outdoor lighting, as in this case most of the light radiated above the horizontal is of little practical use. This method of comparison is nevertheless unfair. If the light is required in a certain direction only, say, for example, below the horizontal, then lamps can be fairly compared by measuring their mean candle-power in this direction, *after all possible means have been taken in each case to concentrate the light in this direction.* The flux of light available to concentrate in the desired direction is known when the M.S.C.P. is known, and the comparative ease with which it can be concentrated can be judged from the study of the distribution curves.

The three constants which should, therefore, be known about a given lamp are: its mean spherical candle-power, its distribution curves, and the number of watts it consumes. These being known, the comparative initial merits of different lamps can be obtained; on general grounds, the best lamp is that which has the highest value of M.S.C.P. per watt; for special purposes, the shape of the distribution curves may alter the relative values of the lamp, and a lamp having a lower value of M.S.C.P. per watt may be better than one with a higher value. It is necessarily assumed that the merits of the lamps in other respects, *e.g.*, suitability of voltage, colour of light, size of light unit, etc., are equal.

Our object being to produce light as economically as possible, the watts per M.S.C.P. should be as low as possible. It is customary amongst lamp-makers to rate their lamps according to the voltage at which they are to be used, their candle-power and the watts per candle-power. Generally, the M.H.C.P. is taken, and frequently the maximum horizontal candle-power; both have values generally higher than that of the M.S.C.P. The consumer who buys a lamp for use on a circuit of given voltage is primarily interested in seeing that it gives the candle-power and consumes the number of watts stated by the maker. Batches of new lamps should, therefore, be tested to verify these two points. If a diagram be drawn, as in Fig. 24, in which for each lamp the value of the candle-power is plotted against the watts, it is possible to see at a glance how uniform are the manufacturers' results. These diagrams are known as target diagrams. The diagram in Fig. 24 is for 16 candle-power lamps. If certain limits be

defined within which it is desirable that all lamps should come, these may be drawn as shown in the figure, and any lamps coming outside the area thus described are deficient for one reason or another. Certain definite limits have been specified for carbon-filament lamps, the only type of

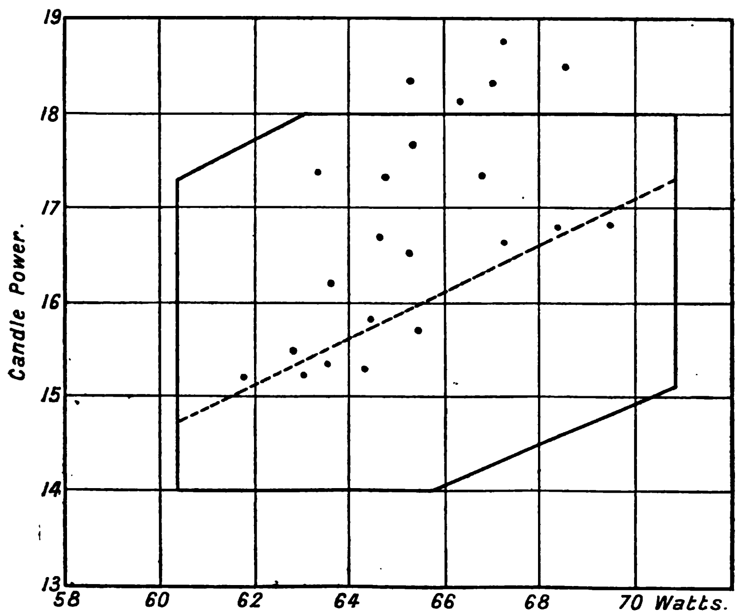


FIG. 24.—Target diagram (16 candle-power lamps).

lamp as yet sufficiently standardised to justify this being done. The target diagram, it should be remembered, is simply a test of the uniformity of the results attained by a given lampmaker or by the class of lamp-makers as a whole; it is not really a particularly good criterion of the value of the lamps.

LIFE TESTS.

In addition to the initial testing of lamps for candle-power, etc., incandescent lamps must be tested for life. The life test generally takes the form of measuring the alteration of candle-power with the number of hours during which the lamp has been burnt. The typical results for modern lamps will be discussed under each type of lamp, but there are certain general questions raised which it is convenient to consider here. The candle-power of an incandescent lamp decreases during its life, and the watts per candle increase, so that there are three ways in which we may define the useful life of the lamp. (1) The useful life may be defined as the number of hours the lamp can be run before it becomes more economical to replace it with a new lamp. (2) The useful life may be taken as the number of hours before the candle-power falls to a certain percentage of its initial value, on the assumption that after this period the lamp no longer gives enough light for the purpose for which it is intended. (3) The useful life may be defined as the number of hours the lamp will run before it actually fails.

Of these the first method is the most scientific, but it is somewhat difficult to realise in practice. The point reached when it becomes more economical to instal a new lamp is known as the "smashing" point: it can be calculated when the rates at which the candle-power falls off and the watts per candle increase, and the cost of the lamp and of electrical energy are known, but the general formula is cumbrous. The principle may be simply illustrated by the following graphical construction. In Fig. 25 A and B are the curves connecting watts per candle and candle-power

respectively with hours during which the lamp has been run. From each of these curves a second curve can be drawn in which the abscissæ represent hours as before,

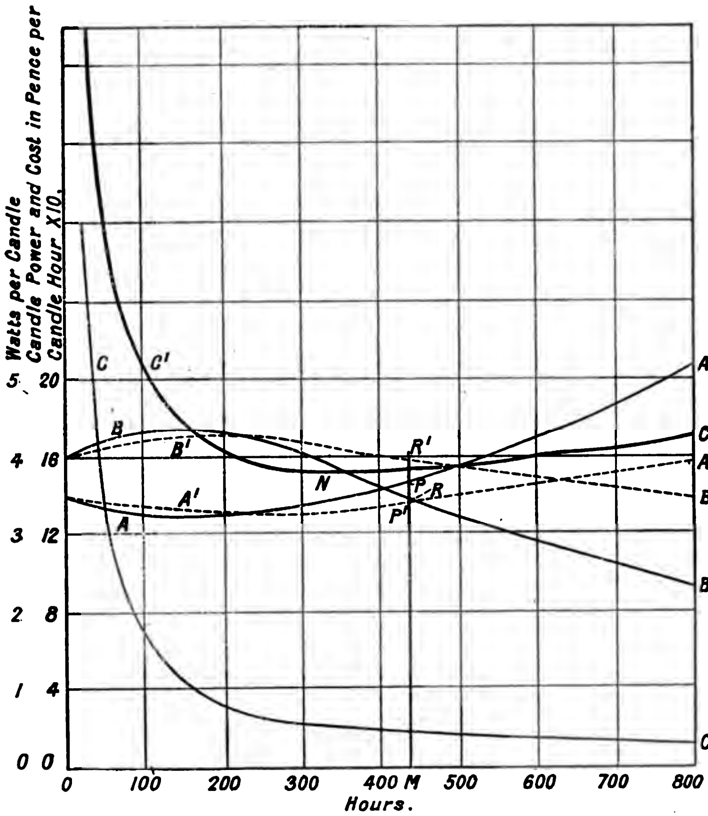


FIG. 25.—Graphical determination of "smashing" point.

but the ordinates represent the *average* watts per candle and *average* candle-power respectively up to the given time. To make this clearer, draw the ordinate M R P. Then M P',

the ordinate of the new curve A′, is made equal to the average height of the curve A up to the point P, and M R′ is made equal to the average height of the curve B up to the point R. In this way the two new curves A′ and B′ are obtained.

Since M P′ is the average watts per candle and M R′ the average candle-power during the time O M, we have

Total candle-hours during O M $= \text{O M} \times \text{M R}'$

Total watt-hours during O M $= \text{O M} \times \text{M R}' \times \text{M P}'$

and cost at *a* pence per watt-hour $= \text{O M} \times \text{M R}' \times \text{M P}' \times a$

$$\therefore \text{Cost per candle-hour} = \frac{\text{O M} \times \text{M R}' \times \text{M P}' \times a}{\text{O M} \times \text{M R}'}$$

$$= \text{M P}' \times a.$$

By drawing a suitable scale, therefore, we can read off directly from the curve A′ the cost per candle-hour for energy after any period. Now suppose a new lamp costs *l* pence. Then, after running for O M hours, the number of candle-hours obtained is O M × M R′, and the cost of the lamp works out, therefore, to $\frac{l}{\text{O M} \times \text{M R}'}$ pence per candle-hour. The values of this expression at various times are readily read off from the curve B′, and can be plotted as a curve C to the same scale of pence as is used for reading the cost per candle-hours for energy from the curve A′. In the actual case illustrated, the cost of energy is taken at 4*d.* per 1,000 watt-hours and the cost of the lamp as 1*s.* The ordinates of the curve C are now added to the corresponding ordinates of the curve A′ and a final curve C′ is thus obtained, which gives the total cost per candle-hour for different times of running. It will be noticed that this curve falls to a minimum at N,

corresponding to a life of about 330 hours, and then rises; the position of the minimum corresponds to the correct smashing point. It is clear that this point will occur later the greater the initial price of the lamp.

In addition to the complexity of this method, a further objection lies in the fact that the smashing point may possibly not be reached until after a time at which the lamp has ceased to give sufficient candle-power to be useful. As, moreover, the useful life determined in this way depends on both the cost of new lamps and the cost of current, it is impossible to make any general statement regarding the useful life of any particular set of lamps. For these reasons the second definition of useful life has been generally adopted, and it is customary to consider that a lamp has become useless when its candle-power has fallen to 80 per cent. of its initial value. This is far from being a completely satisfactory definition, but it has considerable recommendation on the score of simplicity. Partly on account of the general adoption of this definition it is much better, when plotting curves showing the variation of candle-power with life, to plot percentages instead of actual values of candle-power, as in this way curves are obtained, which show at a glance the time at which the 80 per cent. limit is reached and which can be immediately compared one with another whatever the initial candle-powers of the lamps.

The third method of defining useful life is not to be recommended on any grounds except where lamps occur which fail before reaching their useful limit as defined by the second method. There is, however, a general impression that lamps should be run until they fail, and the useful life from the average consumer's point of view is undoubtedly

the life till failure. Too much importance cannot be attached to this point, which is one of the strongest arguments in favour of electric supply companies, supplying and controlling their consumers' lamps in the same way as the gas companies contract for the maintenance of incandescent mantles.

Life tests may be made from several points of view. A test may be carried out to determine the relative merits of different makes of lamps for use on a particular circuit. In this case the lamps must be run on the circuit in question and must be run simultaneously, so that all are subject to the same voltage variations. Or the test may be made to determine generally the relative merits of the lamps; in this case the circuit on which the lamps are tested should be as steady as possible and the voltage of the supply should be automatically regulated or the lamps run off cells. Test results can thus be obtained which are strictly comparable with similar tests made at other times. Unfortunately it is not always possible to deduce from these tests the relative merits of the lamps when run on circuits of varying voltage, such as, notwithstanding Board of Trade regulations, are the rule rather than the exception in this country. No amount of excellent life tests at steady voltage will persuade an engineer that the lamps are good if they do not burn satisfactorily on his own system. It has also been proposed, notably in the Engineering Standards Committee specification for carbon-filament lamps, that life tests should be made at a specified watts per candle instead of at the marked voltage. In this way a better test of the actual qualities of the lamp is obtained, and the result, combined with the result of tests of initial

rating (target diagrams), gives ample means of gauging the relative merits of the lamps. Nevertheless, the test at the marked voltage has several advantages, especially as it is nearer to the actual test the lamp has to undergo in use. The whole question depends simply on the objects with which the tests are carried out, and the particular method adopted must be selected in accordance with these.

One other point may be mentioned here in reference to life testing. It will often be found that the ratio of M.S.C.P. to M.H.C.P. varies during life, and for accurate work account should be taken of this fact. Life tests should be made on the basis of M.S.C.P., but are nearly always made on the basis of the candle-power in a certain direction, or at the best on the basis of M.H.C.P. When the candle-power in one direction only is measured, it is extremely probable that a gradual alteration in the shape of the filament during the test may vitiate the results, especially in the case of metallic-filament lamps where there is a large amount of filament in the bulb very liable to undergo deformation.

CHAPTER V

CARBON-FILAMENT LAMPS

The carbon-filament lamp was developed about the year 1878 as the result of experiments to devise an incandescent electric lamp of comparatively small candle-power. Several experimenters were engaged on this work, and some of them succeeded in obtaining more or less satisfactory results, but the two names which will always be associated with the practical invention of the carbon-filament lamp are those of Edison and Swan. To Edison working in America and Swan in England belongs the credit of having found means of producing an incandescent lamp with a carbon-filament which admitted of the practical commercial development of the invention with results of astonishing benefit to the electrical industry. From the time of its introduction until 1897 this lamp occupied the enviable position of the only incandescent electric lamp on the market. At that date the invention of the Nernst lamp seriously fluttered the electrical dovecots, and all sorts of predictions were rife as to its probable effect on the industry. As time went on, however, it was found that the Nernst lamp, though possessing many advantages, did not seriously compete with the carbon-filament lamp on its own ground, and for another five years comparative peace reigned amongst the lamp manufacturers. The years 1906 and 1907 have brought a number of competitors into the field in the shape of the

various types of metallic-filament lamps, and once again the prospects for the future of the carbon filament are far from rosy, this time with more reason for believing that anticipations will not be falsified.

MANUFACTURE.

The carbon-filament lamp (Fig. 26) consists of a small glass bulb in which is mounted a fine carbon thread or wire. The bulb is exhausted of air and hermetically sealed, and current is led to the filament by two metal wires sealed into the glass. A suitable cap is fixed to the bulb to which the free ends of the leading-in wires are connected; this cap is of standard size so that it can be inserted in a standard lamp-holder.

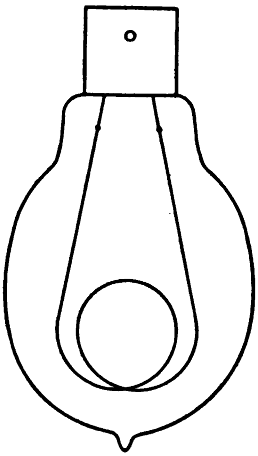


FIG. 26.—Carbon-filament lamp.

The most important part of the lamp is the filament, which is now, to the writer's best knowledge, universally manufactured from a thread of artificial cellulose. This thread is prepared by one or other of the three following methods:—

The Zinc-Chloride Process.—Pure cellulose, such, for example, as cotton-wool or blotting-paper, is dissolved in a concentrated solution of zinc-chloride until a mass of the consistency of treacle is obtained. The process of solution requires great care, and the high purity of all raw materials is essential. The zinc-chloride solution must be accurately standardised for acidity and concentration, the latter being

usually effected by the measurement of the specific gravity, and the humidity of the cellulose must be controlled.

The precise methods adopted to bring the cellulose into solution may vary considerably. It is possible to obtain solution at normal temperatures, but usually the mixture is heated. Much depends on the strength and acidity chosen for the zinc-chloride, but for a particular method of dissolving the limits between which these can vary are very narrow. Experience alone can tell when everything is proceeding smoothly. The first effect of the zinc-chloride solution is to gelatinise the cellulose into a fairly stiff mass, but after a time solution becomes complete and a highly-viscous, clear amber-coloured liquid is obtained. This is filtered by forcing or aspirating the liquid through a suitable filter, such as glass-wool, fine wire gauze, or flannel. It has then to be heated under a vacuum to free the viscous solution from the air carried into it by the cotton-wool or cellulose. After this operation it is ready for squirting. The solution, contained in suitable bottles, is forced by a fairly high pressure through a fine orifice, which just dips below the surface of acidified alcohol contained in a tall glass jar, as in Fig. 27. The alcohol precipitates the cellulose, which forms a fine thread of a diameter depending on the size of the jet, and this thread coils itself up in the bottom of the jar where a glass or china basket is placed to

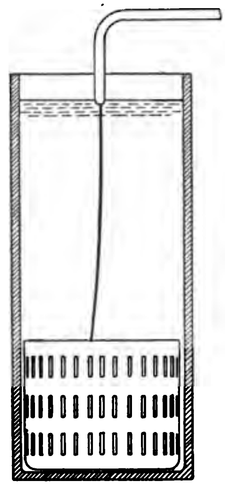


FIG. 27.—Method of squirting cellulose thread.

receive it. If the jar be rotated slowly and the jet set eccentrically, the thread settles in such a manner that a very long length may be obtained without a break and in a condition convenient for subsequent handling. When the basket is full it is lifted out of the jar and put in a bath of acidified spirit to harden the thread further. Two or more successive spirit baths are followed by several baths of dilute acid and finally by prolonged washing in running water. In the initial stages of the washing hydrochloric acid is used to prevent the formation of zinc-oxide in the thread, which after its final washing should be perfectly free from zinc-oxide or salts. It varies according to the method of preparation from a clear, glistening, transparent thread to a somewhat milky, gelatinous one. A final immersion in pure spirit, by removing some of the water, assists drying and also renders the thread somewhat easier to handle whilst winding on to the drying frames.

The Nitro-Cellulose Process.—Tetra-nitro-cellulose (collodion cotton) is prepared from cotton-wool by treatment with nitric and sulphuric acids. The degree of nitration is of importance and should be tested, as the various nitro-celluloses—there are five or more—vary very greatly in solubility in the solvents used. The collodion cotton is dissolved in glacial acetic acid, ammonium carbonate being usually added, as this improves the thread. Solution takes place in the cold and is complete in about twenty-four hours. The solution after filtration is squirted into water by which the nitro-cellulose is precipitated, and the thread thus formed is collected as already described. The thread is thoroughly washed in running water until only pure nitro-cellulose is left. This has now to be denitrated, which

is effected by immersing the thread in a warm bath of ammonium sulphide for several hours. A second shorter immersion in a fresh bath is necessary to effect the thorough denitration, and the thread must then be again thoroughly washed. The denitration requires care and must be very thorough, and is the chief drawback to the nitro - cellulose process, which otherwise possesses many advantages over the zinc-chloride method.

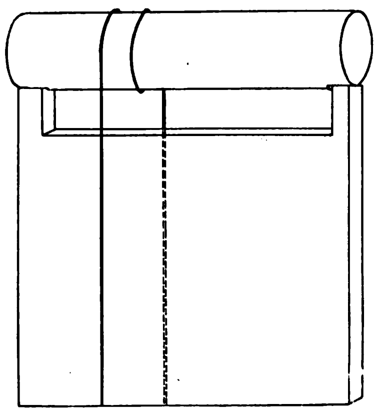


FIG. 28.—Carbon block for shaping filaments.

The Cuprammonium Process.—A solution of oxide of copper in ammonium hydrate dissolves cellulose in the cold, and this method has been used for the preparation of lamp filaments though it is in nothing like such general use as either of the two processes already described. The cellulose is precipitated by dilute acid, and the thread is thoroughly washed before it is ready for drying.

The cellulose thread, produced in any of the above ways, is wound on to large drums or frames to dry. When dry it has much the appearance of catgut in the larger sizes and of silk when of small diameter. It is now ready for shaping to filaments and carbonising. The thread is given the shape which is desired for the final filament by winding it on to blocks as shown in Figs. 28 and 29. These blocks may be of carbon, as in Fig. 28, in which case block and

threads are baked together. With this method, after winding the block, the legs of the filaments are fixed to its sides with wax and the lower ends of the thread cut through so that the filaments may be perfectly free to contract as baking proceeds. Another method is to wind the thread on to metal or porcelain formers, as in Fig. 29, which are dried for some time at about 120° C. It is then possible

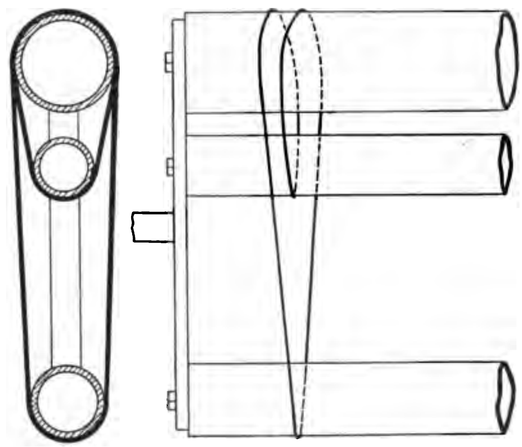


FIG. 29.—Former for shaping filaments.

to draw the bundles of filaments off, as this preliminary heating gives them permanently the shape of the former; the bundles can then be packed loose in the carbonising crucible. In the figures, for the sake of clearness, only one thread is shown wound on the former, but actually a number of threads are wound on side by side in a band ¼ inch to ½ inch wide.

The blocks or bundles of filaments are packed in carbon powder in plumbago crucibles, which are raised to as high

a temperature as possible. The baking divides itself naturally into two parts. During the first the cellulose is decomposed and carbonised, and this part must be carried out with great care. The temperature rise must be perfectly under control, and must proceed steadily at a definite rate, depending on the size of the filaments and the crucibles. Once the thread has been completely carbonised, which occurs when a temperature of about 550° C. is reached, the firing can be continued much more rapidly until the final temperature of about 1,650°—1,700° C. is attained. This is maintained long enough to ensure the crucible having the same temperature throughout. The crucible is then allowed to cool and when cold is unpacked. The final temperature can best be measured by means of Seger cones,[1] but in the earlier stages of the baking a pyrometer, electrical or otherwise, must be used. It is often convenient to carry out the baking in two furnaces corresponding to the two stages, the first being constructed so as to allow of exact regulation of the temperature, and the second designed only for the production of a very high temperature without such accurate control.

The carbonised filaments are gauged for diameter and the legs are cut to the required length, after which they are ready for mounting on to the leading-in wires. Two types of mounts are commonly employed. In the one the filament legs are laid against the ends of the leading-in wires and secured by a drop of paste composed of graphite mixed with

[1] These are small pieces of clay in the shape of a triangular pyramid about two inches long. The cones are made of mixtures of silicates so gradated that the series consists of a number of cones having melting points at intervals of 20° C. The temperature in the oven can be told therefore by the melting of the cones.

a suitable binding material; the paste is afterwards dried in an oven, and sets quite hard and firm. In the other a deposit of carbon is formed over the joint between the wire and the filament by heating this red-hot under benzene. In this type of mount either a butt joint is used or the filament ends are inserted into small tubes formed at the ends of the leading-in wires. To form this deposit the leading-in wires are fixed in two connecting clamps and a short circuiting bar bridged across the filament just above the joints; the whole is then immersed in the benzene bath and a fairly large current passed through the joints from one leading-in wire to the other by way of the short circuiting piece, and this raises the joints to a red heat. The benzene is thereby decomposed and forms a firm coherent deposit of carbon completely round the joint. This type of joint, though more expensive to make, is in many ways superior to the pasted joint.

Some of the filaments now pass through a process known as "flashing." Flashing is for the most part applied only to filaments for low voltage lamps (100 volts and thereabouts), though in some high voltage lamps flashed filaments are used. The filament is placed under a bell jar, which is first exhausted of air and then filled with a hydrocarbon vapour such as coal gas or benzene vapour. The vapour is kept flowing in a gentle stream through the jar and the filament raised to incandescence. As the filament becomes hot the vapour is decomposed and a deposit of carbon forms all over the filament. The thinner parts of the filaments becoming hotter than the rest, receive a heavier deposit of carbon, and thus the flashing produces an even filament from one originally uneven.

The deposited carbon is graphitic in nature and of much lower specific resistance than the carbon of the original filament; in consequence of this and of the increase in diameter the resistance of the filament can be reduced to any desired amount by flashing. The final resistance may be determined in two ways, either cold or hot; if the filaments are flashed to a given cold resistance this must be determined by cutting off the flashing current and measuring the resistance with a Wheatstone bridge, the process being repeated until the correct resistance is attained. Flashing to a given hot resistance is carried out by maintaining a constant potential difference and allowing the current to rise until it attains a certain value, when it is cut off; this can be easily arranged to occur automatically, and in this way one operator can attend to two flashing jars, setting the filament in one whilst the flashing is going on in the other. The resistance of the filament can be checked when cold by a Wheatstone bridge test as in the first method.

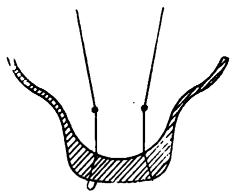


FIG. 30.—Pinch seal.

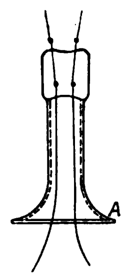


FIG. 31.—Tube seal.

The mounted filaments are next sealed into the bulbs; two types of seal are common, known as the pinch seal and the tube seal. In the pinch seal the leading-in wires are melted into the bulb, which is pinched on to them as shown in Fig. 30. In the tube seal the filament is mounted on to a small tube as in Fig. 31, which is provided with a flange A,

and the bulb is afterwards melted on to this flange. In all sealing-in some part of the leading-in wire is of platinum, though this is usually reduced to a minimum on account of its cost. Platinum is the only metal which makes an absolutely reliable joint with glass, because it has the same coefficient of expansion as glass and does not oxidise during the process of sealing-in. Other metals have been proposed and alloys have been made having the correct coefficient of expansion, but the risk of bad joints with these platinum substitutes is great and has prevented their general adoption. Even when an alloy is used which has the correct coefficient of expansion, or when this difficulty is overcome in some other way there is great liability for the leading-in wire to become oxidised during the process of sealing-in, a leaky joint resulting in consequence.

The lamp bulb has now to be exhausted. Formerly Sprengel pumps only were used for exhausting, but now "chemical" pumping is largely used. The Sprengel pump needs no description; it is slow but very efficient and certain. In chemical pumping a little phosphorus dissolved in alcohol is introduced into the stem before pumping; the lamp is then pumped to as high a degree of vacuum as possible by mechanical pumps; with modern vacuum pumps completely oil-sealed a very high vacuum can be obtained. The stem is then sealed a short way below the bulb and the phosphorus vaporised into the bulb by heating the stem just above the seal thus made. The phosphorus combines with the residual oxygen and completes the exhaustion, and the lamp is then properly sealed off by melting the stem close to the bulb, the familiar little pip on the end of the bulb being thus formed.

Pumping is a difficult and very important part of lamp-making. It is essential during the process of exhaustion to drive off all the gases occluded in the filament and the mounts, and on the inner surface of the bulb. To insure this the bulb must be heated and the filament incandesced; by carefully watching the appearance inside the bulb it is possible to tell when exhaustion is complete. If all the occluded gases are not removed, the vacuum, though good directly after pumping, will deteriorate as the lamp is kept in stock or during use. The vacuum is tested after pumping with an induction coil, a discharge occurring in the lamp pointing to imperfect exhaustion.

The chief test to which the lamps have to be subjected before being issued is that of their candle-power. Methods of photometry vary; lamps may be tested for mean horizontal candle-power by rotating the lamp during the test, or may be photometered in one direction only. The lamp may be classified by either of the following methods. The lamps are run at the correct voltage and the candle-power and watts measured, or they are run at a fixed candle-power and the watts and voltage measured, or at a fixed watts per candle and the voltage and candle-power measured. In any case the lamps have to be subsequently classified according to voltage, candle-power, and watts.

Other tests which are carried out are all for the purpose of preventing the issue of faulty lamps. For example, the lamps are considerably overrun for a short time to see whether any faults in the filaments, such as softness or unevenness, develop. Further tests of the vacuum and a rough test of candle-power (made simply by comparison with a standard lamp of correct voltage and candle-power)

are generally made after capping and marking before the lamps are finally packed.

The process of capping is simple; the brass cap is secured to the bulb by a plaster or cement, the leading-in wires being soldered to the two terminal plates in the base of the cap. Marking with name and candle-power is done by means of hydrofluoric acid or some "ink" composed thereof. Frosting of the bulbs is effected either by sand-blasting or by means of hydrofluoric acid.

It will be seen from the above brief description that the process of lamp manufacture is very complicated and needs careful scientific supervision throughout. Physical and chemical difficulties are encountered at every stage, and it is certainly a triumph of manufacturing organisation that these lamps can be produced by the million with such remarkable uniformity and at such extremely low cost. The most essential part of the process is naturally the filament making, and it will be easily realised that the manufacture of high voltage unflashed filaments of small diameter is especially difficult, as the makers have none of the opportunities of correcting unevenness or wrong size in the filament afforded by flashing. The high voltage filament must come from the furnace perfectly uniform and even in diameter and of exactly the right size to give the required candle-power and watts per candle at the given voltage. The flashed filament can vary between much wider limits as it comes from the furnace, as these can be corrected to a certain extent by flashing. The test of a good lamp is that it shall have a long useful life at a low consumption in watts per candle. Bad filaments, bad mounts, and bad pumping will all militate against this.

The rating test to see that a lamp has its stated candle-power and takes the correct number of watts at the marked voltage is rather the test of careful and conscientious manufacture than a test of the lamp. As only a small percentage of the lamps will be *exactly* correct in this respect, the lamp manufacturer is obliged to work between certain limits which he may vary according as he prefers to reduce the number of his outfalls or to supply a properly rated lamp. Unfortunately, in England the number of nominal supply voltages is small. The following table was given by Mr. C. Wilson, of the Robertson Lamp Works, in the course of a correspondence on this subject.[1]

TABLE VIII.

Declared Pressure.	Number of Stations according to *Electrician* List.	Percentage of Lamps sold at each Voltage.
90	—	0·15
95	—	0·10
100	51	23·00
105	9	4·00
110	8	5·50
115	3	0·40
120	1	1·00
150	2	0·40
195	—	0·05
200	77	17·40
205	5	0·90
210	28	3·25
215	2	0·27
220	81	13·80
225	8	0·64
230	125	10·50
235	—	0·10
240	60	11·40
245	—	0·01
250	10	4·50
Miscellaneous	—	2·63

[1] *The Electrician*, Vol. LVI., p. 936.

It will be seen at a glance that the English manufacturer has no market for his outfalls below 100 volts and 200 volts, only a very small market above 100 volts, and slightly better markets at every 10 volts above 200 up to 240, with, however, scarcely any market at 5 volt intervals. Consider what this means in one case only. The output of Robertson lamps for the year from which these figures were obtained is given by Mr. Wilson as 4,000,000 lamps, so that the output of lamps for 200 volts is, according to the table, 700,000 lamps. Suppose that the outfalls can be all used for either 195 or 205 volts; the market for lamps of these two voltages was 38,000. Thus for every 738,000 200-volt lamps to be made, if 700,000, or 95 per cent., were correct, and 38,000, or 5 per cent., did not fall outside the limits of 5 volts either way, a complete market would exist. In other words, the "yield," as the chemist would express it, of a manufacturing process involving forty or fifty different operations is expected to be 95 per cent.; when the difficulties involved in many of these operations and the fact that a lamp must be sold wholesale for something in the neighbourhood of 6*d.* are remembered, it is not too much to say that such an expectation is absurd. The remedy is simple and will be discussed later in Chapter XII.

PHYSICAL CHARACTERISTICS OF THE CARBON FILAMENT.

The determination of the size of filament for a lamp of given voltage and candle-power depends upon the emissivity or intrinsic brightness and the specific resistance of the filament. Both these properties depend upon the temperature at which the filament is run: the actual temperature

of the filament is difficult to measure, and it is more convenient, therefore, to take some other quantity which can easily be measured as the basis for calculation; the best quantity to take is the consumption in watts per candle. Carbon-filament lamps are manufactured to work at a definite consumption, varying roughly between the limits 3 and 4·5 watts per candle. A lamp consuming 3 watts per candle is a high efficiency lamp, but has only a short life, and one consuming 4·5 watts per candle is of low efficiency but long life. The general value for low voltage lamps may be taken as 3·75 watts, and for high voltage lamps as 4 watts per candle.

The approximate intrinsic brightness of a filament working at various watts per candle may be seen from Table IX.[1]

TABLE IX.

Watts per candle	3·0	3·5	4·0
Unflashed filament. C.P. per sq. m/m of surface	0·89	0·68	0·55
Flashed filament. C.P. per sq. m/m of surface	0·7	0·57	0·45

The specific resistance at the corresponding temperatures is given in Table X.

[1] In calculating the C.P. per sq. m/m of surface it is not the actual surface area of the filament which must be taken, but the area of its projection on a plane perpendicular to the direction in which the candle-power is measured. This follows from the cosine law of emission. (See Chapter III., p. 35.)

TABLE X.

Watts per candle	3·0	3·5	4·0
Unflashed filament. Ohm per *m/m* 1 sq. *m/m* area	0·0167	0·0172	0·0176
Flashed filament. Ohm per *m/m* 1 sq. *m/m* area	0·0146	0·0147	0·0148

None of these values can be given absolutely, as they depend on the method of manufacturing the thread and also largely on the method of carbonising and the final temperature attained. In addition, the process of flashing introduces considerable variations in the specific resistance. It will be seen from Table IX. that the candle-power per square millimetre of surface is less with a flashed than with an unflashed filament. This is due to the alteration of the surface produced by flashing, the deposited carbon having a more or less metallic appearance, whereas the surface of the original filament is matt. This change in the surface is produced as soon as a complete deposit has been flashed on, and increasing the thickness of the deposit does not further alter the nature of the surface. But the deposited carbon has a much lower specific resistance than the original carbon of the filament (about $\frac{1}{10}$) and the final specific resistance of the flashed filament depends, therefore, on the relative cross sections of the unflashed and flashed portions. The thicker the deposit produced by flashing the lower the final specific resistance of the filament.

The calculation of filament sizes is a matter primarily of interest only to the lamp manufacturer, who knows

naturally the value of the constants for filaments of his own manufacture. It will not be necessary to do more than indicate the rules to be followed. Suppose the emissivity of a particular type of filament working at 3·5 watts per candle to be e candles per sq. m/m of surface and its specific resistance under the same conditions to be ρ ohms per m/m cube. Let it be required to make a lamp of voltage V and candle-power C, and let l be the length and d the diameter of the solid round filament necessary. Then we have

$$C = d.\, l.\, e,$$

and

$$\text{Resistance} = \frac{V^2}{3{\cdot}5\ C} = \frac{4\, l\, \rho}{\pi\, d^2}.$$

From these two equations we obtain

$$l = k\, \sqrt[3]{C\, V^2},$$

$$\text{and } d = k' \sqrt[3]{\frac{C^2}{V^2}},$$

where k and k' are constants, as follows:

$$k = \sqrt[3]{\frac{\pi}{14\, \rho\, e^2}}$$

$$k' = \sqrt[3]{\frac{14\, \rho}{\pi\, e}}.$$

Similar formulæ can be deduced for filaments of other than circular cross section. The above formulæ can be applied when the specific resistance of the final filament is known. Calculations involving the determination of the amount of flashed deposit to be put on are more complicated. It may also be mentioned here that when filaments are flashed to a given cold resistance, the cold resistance corresponding to a desired hot resistance depends on

the amount of deposit, since the ratio of hot to cold resistance for the deposited and the original carbon is different.

It is of interest to study the laws connecting the variations of potential difference, candle-power, resistance,

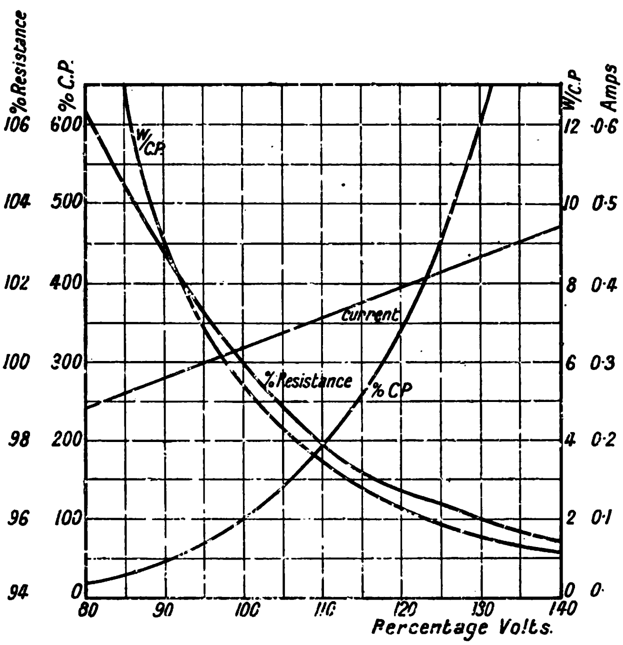


FIG. 32.—Characteristic curves for carbon-filament lamps.

current and watts per candle for carbon filaments. As the variations of all these quantities are produced practically by altering the potential difference at the lamp terminals, it is most convenient to examine the variation of each when the potential difference is altered. In Fig. 32 are given curves showing the variation of candle-power, current,

resistance and watts per candle, with variations of P.D. for an 100-volt 8 candle-power lamp with flashed filament. The abscissæ represent percentage values, and so also do the ordinates of the candle-power and resistance curves. This makes comparison of the curves and their application to lamps of other voltage and candle-power simpler.

It will be seen from these curves that the resistance decreases with a rise in temperature (consequent upon the increased current due to increased voltage), and the candle-power increases very rapidly with increase of voltage, and the watts per candle diminishes rapidly. This is one of the great disadvantages of the carbon filament, that a small increase of voltage produces a great diminution in watts per candle. The variation in candle-power is a matter of less, though considerable, importance. If lamps are used on a circuit the voltage of which is consistently lower than its nominal value, the diminution in candle-power is likely to cause dissatisfaction to the consumer, who will, however, probably not grumble on this score when the voltage is consistently high. But the alteration in watts per candle, though the consumer is unable to perceive it, is in reality much more to his disadvantage. When the voltage is too low he is paying far more per candle-hour than he should be, and when the voltage is too high his lamps are wearing out much too fast. It must not be supposed that these evils are unlikely to occur in practice. Unfortunately it is only too frequently the case that supply voltages vary considerably from their nominal values. Not only is the voltage on the average higher or lower than it should be, but it varies considerably from time to time, often exceeding the 4 per cent. limit legally allowed. With

the carbon-filament lamp every increase of voltage produces an increase of temperature highly deleterious to the life of the lamp.

Light Distribution with Carbon-filament Lamps.

The curves of light distribution for carbon-filament

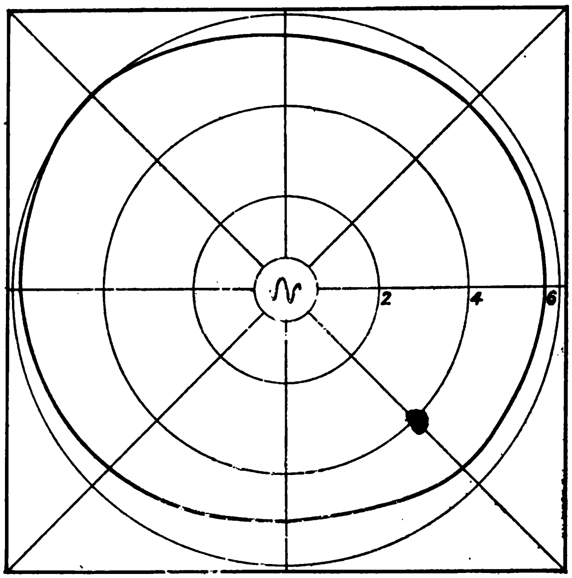


Fig. 33.—Horizontal distribution curve. Single loop carbon-filament lamp.

lamps depend somewhat upon the shape of the filament, to a smaller extent on the shape of the bulb, and also on whether the bulb is frosted or not. On account of the numerous shapes of filament and bulb in use it is impossible to give a comprehensive collection of distribution curves, but typical curves for a lamp with single loop

filament are given in Figs. 33 and 34. In Fig. 33 is shown the horizontal distribution curve for this lamp, and in Fig. 34 is shown the vertical distribution curve. In Fig. 35 are given the vertical distribution curves for a lamp with clear bulb, and for a similar lamp with frosted bulb. It will be noticed that the frosting makes the distribution slightly more uniform. In all cases the distribution with

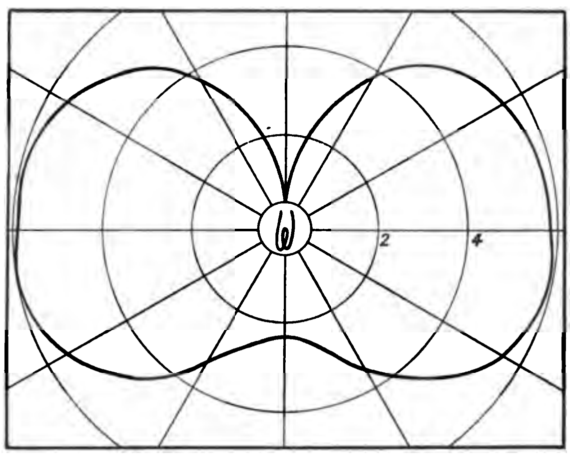


FIG. 34.—Vertical distribution curve. Single loop carbon-filament lamp.

the carbon-filament lamp is fairly uniform and satisfactory for general purposes. Where special need exists for concentration of the light in particular directions, special shaped filaments can be designed or, better, reflectors can be used. The most marked defect of the distribution with the usual shaped filaments is that too little light is given in downward directions, and for this reason shades, such as the common conical opal glass shade, are generally used above the lamp.

Life of Carbon-filament Lamps.

During use the carbon-filament lamp generally undergoes the following changes. At first the filament decreases in resistance, causing an increase in the watts consumed by the lamp, a rise in its candle-power and a fall in the watts per candle. This change is due to a continuance of the

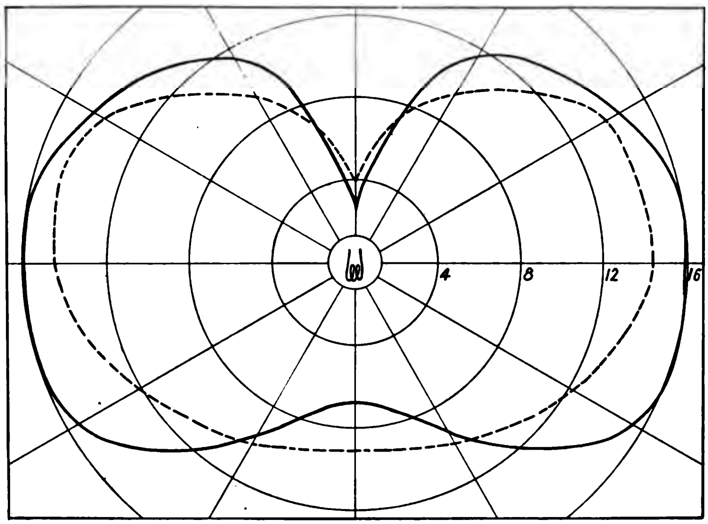


Fig. 35.—Vertical distribution curves. Carbon-filament lamps. *Full curve,* clear bulb. *Dotted curve,* frosted bulb.

baking of the filament, or to use a term which has recently become general in connection with metallic-filament lamps, to a "sintering" process, whereby the particles of the filament become more compactly welded together. This change is gradual, and may probably continue throughout the life of the lamp, but after a time, varying with the individual lamp, is masked by other changes which occur. These are

the gradual disintegration or sublimation of the filament, and the blackening of the inside surface of the bulb. The disintegration of the filament causes its resistance to increase, and its surface to become less polished and consequently a better radiator; from both causes there results a diminution in the candle-power and an increase in the watts per candle. Both these alterations are intensified by the blackening of the inside surface of the bulb, due, it is generally believed, to the deposition thereon of the carbon particles thrown off from the filament.

The useful life of a lamp, defined as the life until the candle-power has fallen to 80 per cent. of its initial value, depends on the watts per candle at which it is worked and on the perfection with which the lamp has been made. The lower the consumption in watts per candle the shorter the useful life of the lamp; when the watts per candle are very low it is probable that the filament will fail before the 80 per cent. limit is reached, but with normal efficiencies the 80 per cent. limit is usually reached long before the filaments fail. Life test curves vary immensely from one make of lamp to another, and also very greatly from one batch to another of the same make. It is useless to make tests on a single lamp, the average results of at least five should always be taken, and if any attempt to judge a large batch of lamps is being made the average of a larger number must be taken. If the object of the test is simply to judge the merits of the batch of lamps, it is best to pick out a certain percentage at random and test the lamps at the marked voltage, as this will give the best indication of the results to be expected from the whole batch. But if a test is to be made for the purpose of comparing different

makes of lamps, a somewhat different procedure should be adopted. A test should first be made of the rating by testing a large number of lamps of each make for candle-power and watts per candle at the marked voltage. A sufficient number of lamps of each make should then be picked out for life test, all taking as nearly as possible the same watts per candle at the given voltage; the test on these lamps affords a better criterion of the relative merits of the different makes, considered purely from the technical point of view. Combined with the rating test, it gives also a fair idea of the relative practical values of the lamps, though the test of a number of lamps picked at random and run at the marked voltage gives this result more quickly and more satisfactorily. It is clearly of little value to know that lamps of make A are better than lamps of make B when run at, say 3·75 watts per candle, when, as is possible, lamps of make A vary from 3·5 to 4·5 watts per candle, while those of make B vary only from 3·6 to 3·9 watts per candle.

Life test curves should always show the alteration in candle-power and in watts per candle; if the average candle-power and watts per candle throughout the life are found from the curve it is possible to calculate for each make of lamp the cost per candle-hour, and that lamp for which this is lowest must be judged to be the best. The calculation is perfectly simple.

Let—

Cost of lamp in pence	$= a$
Average life in hours	$= h$
Average candle-power	$= c$
Average watts per candle	$= w$

And cost of Board of Trade Unit (1,000 watt-hours) in pence $= b$

Then we have—

Total energy consumed $= c.\ w.\ h$ watt-hours

Total candle-hours $= h.\ c$

∴ Lamp cost per 1,000 candle-hours $= \dfrac{1{,}000\ a}{h\ c}$

Energy cost per 1,000 candle-hours $= 1{,}000 \times \dfrac{c\ w\ h}{h\ c} \times \dfrac{b}{1{,}000}$

$= b\ w$

And the total cost per 1,000 candle-hours $= \dfrac{1{,}000\ a}{h\ c} + b\ w.$

TABLE XI.

Make of Lamp.	A.	B.	C.	D.
Cost of lamp	9*d.*	10*d.*	0*d.*	19*d.*
Average life in hours	1,000	400	2,000	800
Average C.P.	14·5	13	15	14
Average W./C.P.	4·0	3·5	5·0	3·75
Cost per 1,000 C.P. hours at 2*d.* per unit	8·62	8·92	10	9·2
,, 4*d.* ,,	16·62	15·92	20	16·7
,, 6*d.* ,,	24·62	22·92	30	24·2
,, 8*d.* ,,	32·62	28·92	40	31·7

In Table XI. some examples are worked out to show that the cheapest lamp to use varies with the cost of current.

As will be seen, lamp A is the cheapest to use when current costs 2*d.* per B.T.U., but is dearer than lamp B when current costs 4*d.*, 6*d.*, or 8*d.*, and dearer than lamp D when current costs 6*d.* or 8*d.*, in spite of the fact that lamp D costs initially more than double lamp A. Lamp C is dearer than any of the others, even though its initial cost is taken

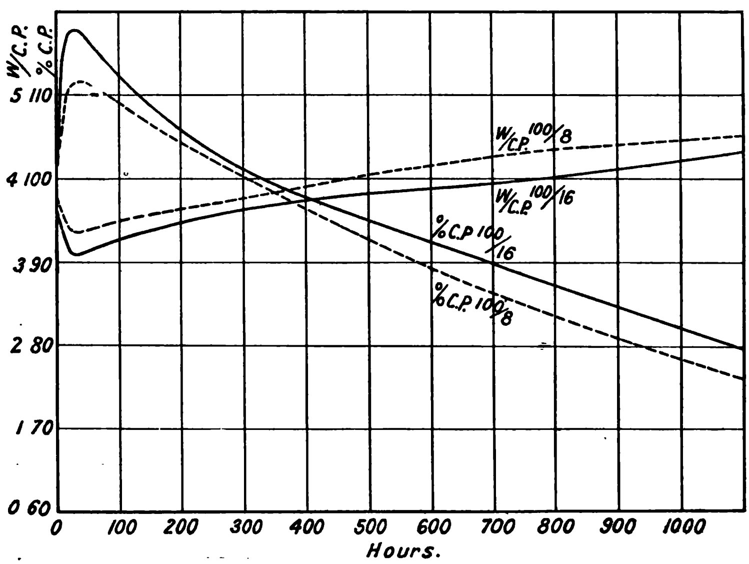


FIG. 36.—Life test curves for 100-volt carbon-filament lamps.

as nothing, and it has been credited with a very long life. It does not pay to use such a lamp even if it is presented to the user.

In Figs. 36 and 37 are given some typical life test curves for modern 100-volt 8 candle-power and 16 candle-power and 200-volt 8 candle-power and 16 candle-power lamps. The initial rise in candle-power is clearly seen in each case.

The average values of life, candle-power, and watts per candle obtained from these curves are as given in Table XII.

TABLE XII.

	Average life.	Average C.P.	Average W./C.P.
	Hours.		
100 volt 8 c.p. .	900	7·5	4·0
100 ,, 16 ,, .	1,100	14·9	3·8
200 ,, 8 ,, .	900	7·4	4·7
200 ,, 16 ,, .	1,100	15·2	4·4

Various attempts have been made to find a relation between the life of carbon-filament lamps and the watts per

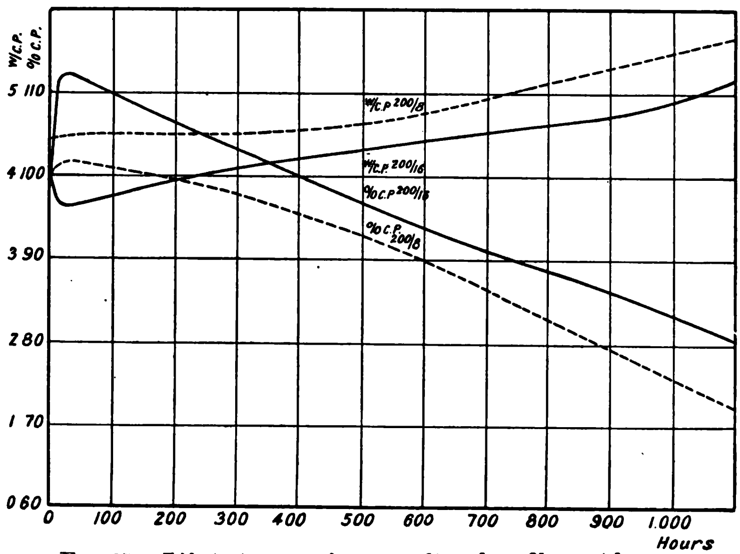


FIG. 37.—Life test curves for 200-volt carbon-filament lamps.

candle-power at which they are run. It is doubtful whether any very definite relation can be found and fairly certain that the relation for lamps of one make cannot be directly

applied to lamps of another make. When the limits between which the watts per candle are varied are near together, the connection between life and watts per candle can be more definitely stated, but when lamps are greatly overrun the results obtained are less satisfactory. For the purpose of quickly obtaining life test results it would be

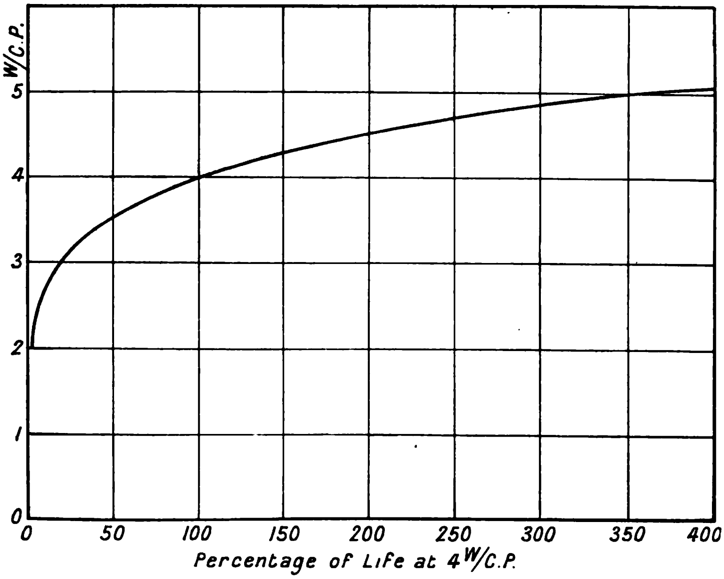


FIG. 38.—Relation between life and consumption in watts per candle.

convenient to carry out tests at a voltage considerably above normal, say such that the lamps are working at 2—2·5 watts per candle; but results obtained in this way should only be applied with great caution. For manufacturing tests in which all the lamps are made by the same method, it is possible to carry out quick tests in this manner. In Fig. 38 is given a curve which connects approximately the

useful life and the watts per candle; this curve may be taken as roughly true, at any rate, within the limits of the efficiencies normally used. Instead of showing the actual values of life at different consumptions in watts per candle, the percentage value of the life at 4 watts per candle is

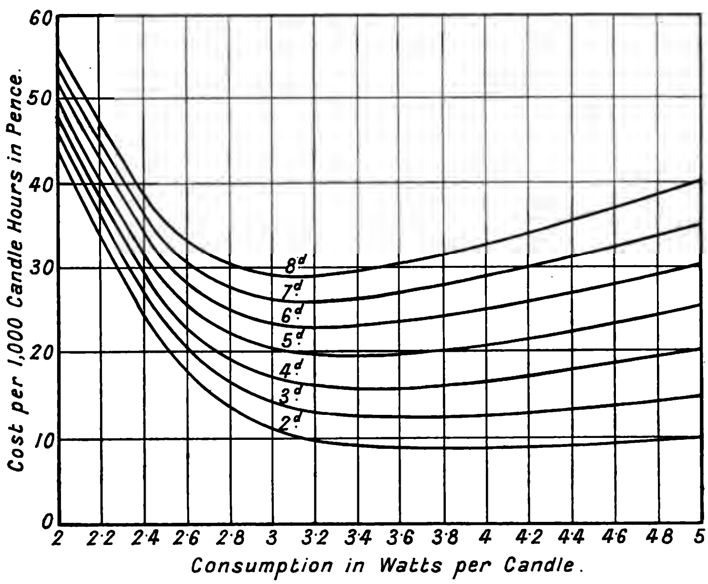


FIG. 39.—Total cost and consumption in watts per candle for various energy costs.

shown. Assuming that the normal life of a 4-watt lamp is 1,000 hours, curves may be calculated showing the cost per 1,000 candle-hours (energy and lamp renewals) at different efficiencies, with energy at various prices per unit and lamps at various prices. One set of such curves is shown in Fig. 39; for these curves the cost of the lamp was taken at 1*d*. per candle (*i.e.*, 16*d*. for a 16 candle-power

lamp, 8*d.* for an 8 candle-power lamp, etc.). The curves show, using lamps at this price, the cost in pence for 1,000 candle-hours, with energy at prices from 2*d.* to 8*d.* per unit.

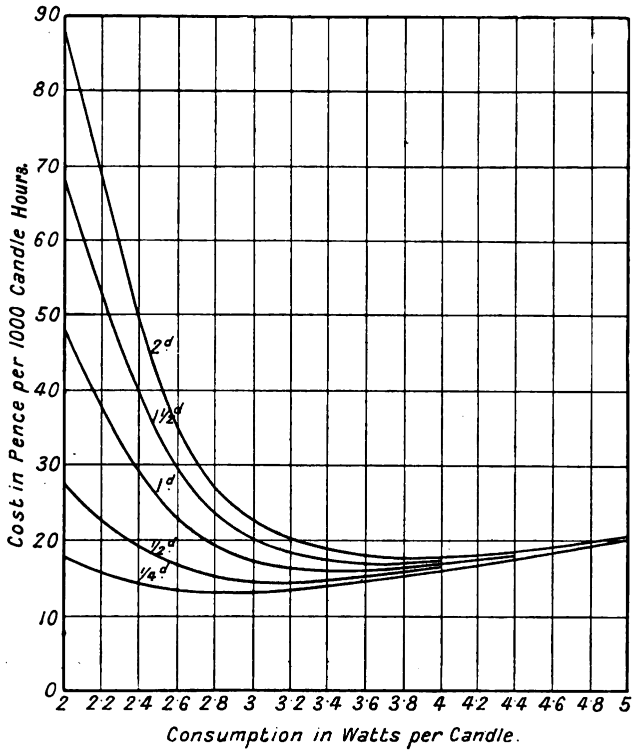


FIG. 40.—Total cost and consumption in watts per candle for various lamp costs.

Similar curves can be drawn for other lamp prices; they are similar in shape to the curves in Fig. 39, but when the price of the lamp is less than 1*d.* per candle they are flatter, and the initial high part of the curve is much less

marked; when the cost is over 1*d.* per candle, the curves are more markedly U-shaped, the initial high part being more strongly marked. This is shown by the curves in Fig. 40, which shows a set of curves for different prices per candle at one price per unit.

It will be noticed that all the curves in Fig. 39 fall to a minimum value and then rise. Thus when energy costs

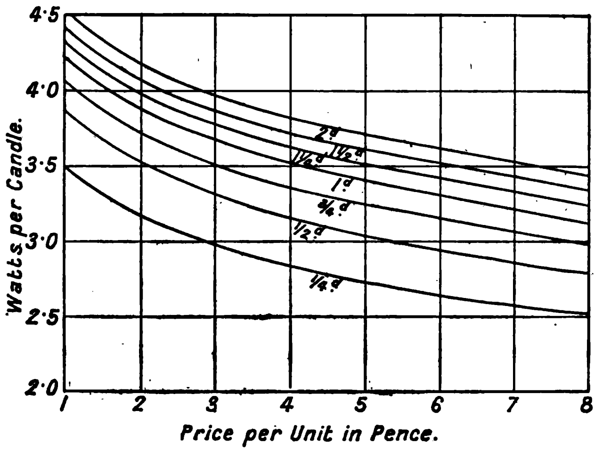


FIG. 41.—Most economical consumption in watts per candle for carbon-filament lamps.

5*d.* per unit, the minimum cost per 1,000 candle-hours is 19*d.*, and this value is obtained when the lamps are run at 3·4 watts per candle. By taking the value of the watts per candle at the minimum from all these curves, and from the corresponding curves for other lamp costs, we obtain the set of curves in Fig. 41. These show the consumption in watts per candle at which lamps should be run in order to obtain light most cheaply for varying prices of energy and lamps. Thus a 16 candle-power lamp, costing 1*s.* (*i.e.*, ¾*d.*

per candle), should be run at 3·5 watts per candle when energy costs 3*d*. and at 3·2 watts per candle when energy costs 6*d*. per unit. An 8 candle-power lamp, costing 1*s*. (*i.e.* 1½*d*. per candle), should be run at 3·9 watts per candle when energy costs 3*d*. and at 3·55 watts per candle when energy costs 6*d*. per unit.

It will be seen that the cheaper the lamp and the higher the cost of energy the lower is the best value of watts per candle. As also the cost of an 8 candle-power lamp is generally about the same as that of a 16 candle-power, it will be seen that as a general rule the higher the candle-power of the lamp the better it is to run it at a low value of watts per candle.

The actual costs per 1,000 candle-hours and the absolute values of watts per candle obtained from these curves must only be regarded as approximately correct, as they depend on the correctness of the curve in Fig. 38 and on the assumed life of 1,000 hours for a 4-watt lamp, but the general laws which these curves illustrate are correct under all conditions. Figures showing the actual cost per 1,000 candle-hours at certain fixed consumptions in watts per candle are given in Table XIII.

The useful life of lamps in frosted bulbs is always considerably less than that of lamps in clear bulbs. The reasons given for this have been various, and until quite recently it cannot be said that the phenomenon was properly understood. Some experiments published by Messrs. Cravath and Lansingh,[1] showed that the useful life of a frosted lamp was only 48 per cent. of that of a clear lamp. The conditions under which the experiments

[1] *The Electrician*, Vol. LVII., p. 293, June 8, 1906.

were carried out did not admit of the cause of the diminution of life being determined, but a number of experiments suggested by this paper have since been carried out in America which throw considerable light on the problem.

The fall in candle-power of a clear lamp is due to

TABLE XIII.

TOTAL COST OF LIGHTING PER 1,000 CANDLE-HOURS. CARBON-FILAMENT LAMPS.

Cost per B. O. T. Unit.		1*d.*	2*d.*	3*d.*	4*d.*	5*d.*	6*d.*	7*d.*	8*d.*
	W./C.P.	*d.*	*d.*	*d.*	*d.*	*d.*	*d.*	*d.*	*d.*
Lamps costing ½*d.* per candle, *e.g.*, 16 c.p. lamps at 8*d.*	3·0	5·75	8·75	11·75	14·75	17·75	20·75	23·75	26·75
	3·5	4·65	8·15	11·65	15·15	18·65	22·15	25·65	29·15
	4·0	4·5	8·5	12·5	16·5	20·5	24·5	28·5	32·5
	4·5	4·75	9·25	13·75	18·25	22·75	27·25	31·75	36·25
Lamps costing 1*d.* per candle, *e.g.*, 16 c.p. lamps at 1*s.* 4*d.*	3·0	8·5	11·5	14·5	17·5	20·5	23·5	26·5	29·5
	3·5	5·8	9·3	12·8	16·3	19·8	23·3	26·8	30·3
	4·0	5·0	9·0	13·0	17·0	21·0	25·0	29·0	33·0
	4·5	5·0	9·5	14·0	18·5	23·0	27·5	32·0	36·5
Lamps costing 1½*d.* per candle, *e.g.*, 8 c.p. lamps at 1*s.*	3·0	11·25	14·25	17·25	20·25	23·25	26·25	29·25	32·25
	3·5	6·95	10·45	13·95	17·45	20·95	24·45	27·95	31·45
	4·0	5·5	9·5	13·5	17·5	21·5	25·5	29·5	33·5
	4·5	5·25	9·75	14·25	18·75	23·25	27·75	32·25	36·75
Lamps costing 2*d.* per candle, *e.g.*, 8 c.p. lamps at 1*s.* 4*d.*	3·0	14·0	17·0	20·0	23·0	26·0	29·0	32·0	35·0
	3·5	8·1	11·6	15·1	18·6	22·1	25·6	29·1	32·6
	4·0	6·0	10·0	14·0	18·0	22·0	26·0	30·0	34·0
	4·5	5·5	10·0	14·5	19·0	23·5	28·0	32·5	37·0

three causes: the alteration of the filament, the blackening of the bulb, and the outside of the bulb becoming dirty. The last cause is in general negligible, as the bulb of a clear lamp is easily cleaned. With a frosted lamp, however, the bulb cannot be so easily cleaned, and indeed generally becomes to a certain extent discoloured. There

is thus one reason for the shorter useful life of the frosted lamp. In addition, it has been suggested that both the deterioration of the filament and the blackening of the bulb proceed more rapidly with frosted lamps on account of the higher temperature of the bulb. There is no doubt that when a lamp is run under conditions which prevent the bulb cooling its useful life is greatly diminished, and blackening takes place very rapidly. Whether the difference in temperature between a clear and a frosted bulb is sufficiently great to produce an appreciable effect on the life of the lamp has not been definitely determined, but there is no doubt that even slight differences in temperature are important in this respect. If lamps are used in hot situations, for example, in the near neighbourhood of a fire grate, their lives are considerably shortened: a striking case occurs with lamps used in baking ovens which have very short lives. For this reason it is most desirable that all shades and globes should provide efficient ventilation so that the lamps may keep cool. This fact is so little recognised that it would not be far from the truth to say that the great majority of shades and globes seem to have been specially designed so that the lamp burns in as hot an atmosphere as possible, although the provision of two or three small ventilation holes is all that would be necessary to avoid this defect. This criticism applies with special force to shades for lamps burning in clusters.

A third cause has been brought to light by the experiments already referred to made by Mr. E. P. Hyde,[1] and by Mr. P. S. Millar,[2] and has been discussed theoretically by Dr.

[1] See *The Electrician*, Vol. LIX., p. 233, May 24, 1907.

[2] See *The Electrical World*, Vol. XLIX., p. 798, April 20, 1907.

A. E. Kennelly.[1] This is the absorption due to the deposit on the globe being greater in a frosted lamp. When light from a filament passes through a clear globe most of it passes straight through, and only a very small percentage is reflected back into the lamp; with a frosted globe, however, a large percentage of the light is reflected from the frosted surface back into the bulb and only finally escapes after repeated reflections to and fro; at each reflection there is absorption of a percentage of the light as it passes through the deposit on the inner surface of the bulb, and hence a deposit of given thickness will absorb a much higher percentage of the light when the bulb is frosted than when it is clear. Messrs. Hyde and Millar both showed that this was the case by determining the absorption produced by frosting new and old lamps. When new lamps were frosted an absorption of from 4 to 6 per cent. was produced. Frosting lamps in which the initial candle-power had fallen 12 per cent. occasioned an absorption of about 14 per cent., and frosting lamps which had fallen 20 per cent. occasioned an absorption of 18—19 per cent. It thus appears that the frosting occasions an additional absorption in the black deposit of about 18 per cent. when the deposit is such as is formed at the end of the useful life of an unfrosted lamp. Mr. Millar divides the total candle-power diminution into the following parts: alteration in filament, 3 per cent.; blackening, 5 per cent.; additional absorption in deposit due to presence of frosting, 6 per cent.; dust factor, 7 per cent. Round figures are given as the actual values can only be applicable to the particular case. Further experiments on this point are

[1] *The Electrical World*, Vol. XLIX., p. 987, May 18, 1907.

desirable, and Mr. Hyde is now carrying out a very complete set. It is particularly desirable to separate the absorption due to dust, as this, even if unavoidable, is obviously unconnected with the actual burning hours of the lamp, and it would be interesting to determine, if possible, whether or not the blackening and the deterioration of the filament do actually proceed more rapidly in a frosted bulb.

Rating of Carbon-filament Lamps.

The use of the target diagram for testing the initial rating of carbon-filament lamps has already been explained. The limits allowable have until recently varied according to the views of the individual making the test, but the recently issued "British Standard Specification for Carbon-filament Glow Lamps," drawn up by a sub-committee of the Engineering Standards Committee, is likely to lead to more uniformity in this respect. The standard specification recognises four classes of lamps: A, 110-volt, 400-hour; B, 220-volt, 400-hour; C, 110-volt, 800-hour; and D, 220-volt, 800-hour. In each class there are five standard candle-powers, namely, 8, 12, 16, 25 and 32. In testing a consignment of lamps at least 5 per cent. (and in any case not less than twenty lamps) are to be tested for initial candle-power and total watts, and 90 per cent. of these must fall within certain specified limits. The candle-power is the M.H.C.P. (pentane standard) determined by revolving the lamp at 200 r.p.m. Five per cent. of the lamps tested for rating are to be subjected to life test, which is to be carried out at a certain standard initial watts per candle instead of at the marked voltage, and the voltage must not vary more than ½ per cent. up or down during

test. From the life test curve the total candle-hours are calculated, any area above a line $6\frac{1}{4}$ per cent. above standard candle-power being neglected. The average total candle-hours must be not less than 90 per cent. of certain standard values given, and the average M.H.C.P. not less than 90 per cent. of the standard candle-power. Provision is made for carrying out life tests at standard pressure, in which case the total candle-hours and the useful life are to be taken as 75 per cent. of the corresponding figures for life at fixed watts per candle; the useful life will, therefore, be 300 and 600 hours respectively.

The part of this specification which relates to initial rating is likely to prove more valuable than the part relating to life tests, owing to the general impossibility of observing the necessary precautions. The specification also covers several other important points, such as the size of cap, the insulation resistance, etc.

Standard Carbon-filament Lamps.

The suitability of carbon-filament lamps for use as secondary standards has already been pointed out. Any carbon-filament lamp can be so used, but it is evident from what has preceded that many precautions are necessary in its use. To overcome some of the more troublesome objections, Prof. Fleming has designed a lamp which he described in a paper read before the Institution of Electrical Engineers.[1] The chief features of this lamp are that the filament is previously "aged" by being run until the initial rise in candle-power is at an end; it is then removed and mounted in a large flat-sided bulb. The blackening of a

[1] *Journal of the Institution of Electrical Engineers*, Vol. XXXII., p. 132, 1903.

large bulb takes place much more slowly than that of a small bulb, and as the initial alterations in the filament are passed the lamp will remain constant in candle-power for a long period. The filament is worked at a fairly low efficiency, the consumption being about 4·5 watts per candle. In Mr. Paterson's paper[1] some life curves are given showing the behaviour of these lamps. The curves show that with low voltage lamps the candle-power remains on the whole extremely constant, but the curves for high voltage lamps are far from satisfactory.

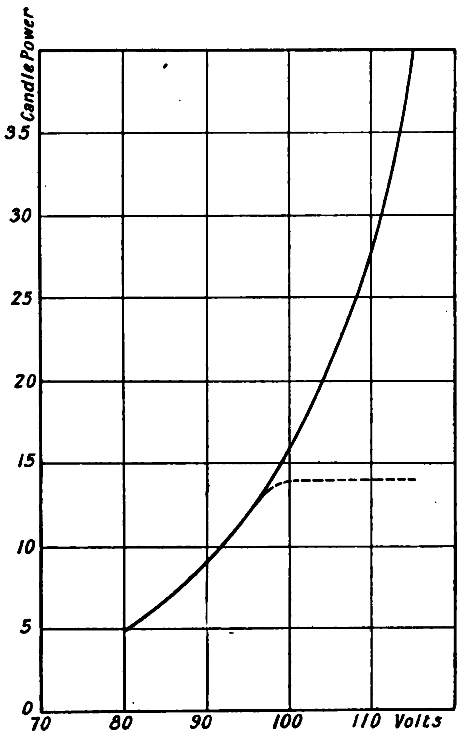


FIG. 42. — Candle-power characteristic for carbon-filament lamp.
Full curve, lamp only. *Dotted curve*, lamp with iron series resistance.

As it is possible, however, always to keep one lamp as a reference standard, which is very rarely used, these lamps are extremely useful for general photometric purposes.

[1] *Journal of the Institution of Electrical Engineers*, Vol. XXXVIII., p. 271.

The chief objection to the use of the carbon-filament lamp as a standard is the great variation of candle-power with a small change in voltage, and the necessity, therefore, for very accurate means of measuring and controlling the voltage. It is common practice to overcome this difficulty by using as standard a lamp of the same voltage as the test lamp and connecting both in parallel across the supply, so that any variations in voltage affect both equally. This method assumes that in the two lamps the variation of candle-power with voltage obeys the same law, which is not necessarily true. This only partially gets over the difficulty, as the initial standardisation of the working standard still involves the use of a potentiometer or other very accurate instrument for measuring the voltage. The writer suggested some years ago the use of the iron resistances used with the Nernst lamps (see next chapter) in conjunction with the working standard, as these minimise very greatly the effect of variation in voltage, and has himself found this a very convenient and useful arrangement. In Fig. 42 is given a curve showing the variation in candle-power of a carbon-filament lamp connected in series with two of these resistances when the supply voltage is varied over a considerable range. The variation in candle-power for a similar lamp run direct off the supply is also shown. It will be seen that at 105 volts variations of 5 per cent. of the supply voltage, up or down, are without appreciable effect on the candle-power of the lamp in series with the resistances.

Improvements in Carbon-filament Lamps.

It is a melancholy fact to have to record that beyond detail improvements in methods of manufacture there have

been, with one exception, no radical alterations in the carbon-filament lamp since its invention. The early years of manufacture were naturally full of progress in detail,

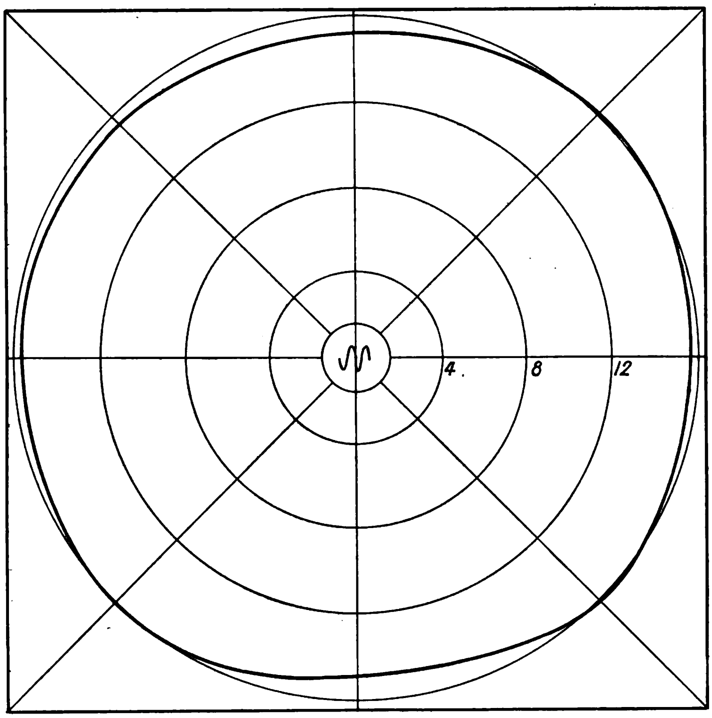


FIG. 43.—Horizontal distribution curve. Double horseshoe metallised carbon-filament (Gem) lamp.

the most striking advance being in the methods of preparing the thread. The original carbon-filament lamps were made from naturally occurring materials, such as bamboo-fibre and cotton. Swan's process of parchmentising the cotton was a big advance, but this and all

the older methods gave way before the zinc-chloride and other processes of forming artificial cellulose threads. Recent years have also seen a considerable development in the design of filaments and lamps for special purposes, as an example of which may be quoted the tubular lamps used

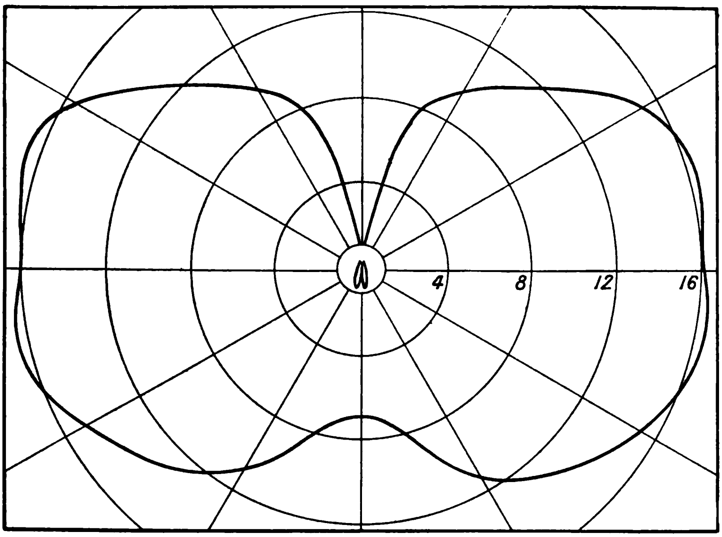


FIG. 44.—Vertical distribution curve. Double horseshoe metallised carbon-filament (Gem) lamp.

in the Linolite and similar systems, but none of these improvements are of a radical nature. The only improvement deserving that name is that brought forward by Mr. J. W. Howell, of the General Electric Company of America, in 1905,[1] Carbon filaments prepared in the usual way are electrically baked to as high a temperature as possible; they are then flashed and afterwards again baked to a temperature between

[1] *The Electrician*, Vol. LV., p. 588, July 28, 1905.

3,000° C. and 3,500° C. This treatment produces a remarkable change in the nature of the filament. The temperature coefficient of resistance from being negative becomes positive. The cold resistance falls to about $\frac{1}{5}$ of its initial value, and

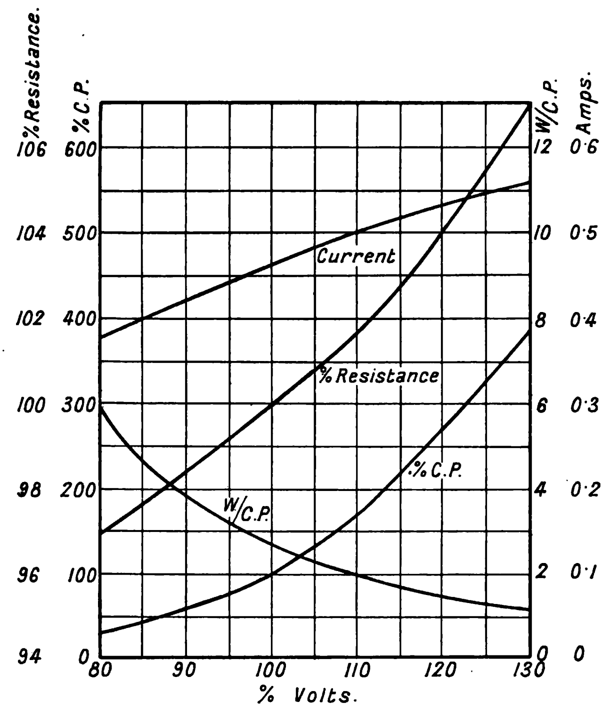


FIG. 45.—Characteristic curves for metallised carbon-filament lamps.

the hot resistance to about $\frac{5}{6}$. The bulk of the change appears to take place in the carbon deposited by flashing, and this assumes a metallic appearance and consistency which led the inventors to call the filament a metallised carbon filament. It is stated that this filament throws off

carbon much less readily than ordinary filaments, and that in consequence it produces much less blackening on the bulb. A useful life of 500 hours is said to be attainable when working at 2·8 watts per candle. The alteration in sign of the temperature coefficient is undoubtedly a most valuable property, as it must produce much greater stability of the filament when run on circuits of varying voltage; the decrease in specific resistance is, however, a disadvantage, especially as an initially flashed filament has to be used. This means the practical limitation of the improvement to the low voltage lamp. Although it is some years now since its first introduction, the lamp has only recently been introduced into this country by the British Thomson-Houston Company, who have put lamps of 16 candle-power for voltages from 100 to 125 on the market. Distribution curves for one of these lamps are given in Figs. 43 and 44, and in Fig. 45 (which may be compared with Fig. 32) are shown the variations of candle-power, watts per candle, current and resistance, with variation of voltage. The recent developments of metallic-filament lamps must necessarily militate greatly against the success of this improvement, which is nevertheless of special interest as showing that there may still be undreamt-of possibilities latent in the carbon-filament lamp.

CHAPTER VI

THE NERNST LAMP

THE first patents covering the principle of the Nernst lamp were taken out by Prof. W. Nernst in 1897 and 1898, and the lamp was first introduced into this country in 1899 by Mr. Swinburne, who read a paper describing it before the Society of Arts in February of that year. The Nernst lamp, as it was at that date, was only a very crude lamp, the progress that had been made in its development amounting to little more than showing that Nernst filaments could be made, which, whilst consuming only about half as much power per candle as carbon filaments, had nevertheless a reasonably long life. Much further experiment was needed before a commercial lamp could be produced, and the difficult task of carrying this out was taken up vigorously in England, Germany, and America by the three companies interested, their efforts being crowned with success towards the end of 1900. Each company, though proceeding on somewhat different lines, succeeded in perfecting a satisfactory type of lamp, but the English company never manufactured on a commercial scale, and, for reasons connected with the ownership of the English patents, finally abandoned altogether the intention of so doing. The lamp, as it is constructed to-day and sold in England, is, therefore, that developed and manufactured by the Allgemeine Elektricitäts Gesellschaft, of Berlin.

It has undergone but little modification since the first satisfactory types were produced in 1900 and 1901, and it has decidedly failed to achieve the results anticipated at its first introduction, though it has proved a useful and undoubted improvement in many respects.

The essential feature of the Nernst lamp is the employment, as the incandescent body, of an electrolytic conductor. This filament, or glower, as it has been termed, is a short rod composed of a mixture of certain oxides; such a body is not an electrical conductor when cold, but on being heated conducts fairly well. Means have to be provided in the lamp, therefore, for raising the glower to the temperature at which it conducts; this is effected by the use of an electrical heating coil, or heater, fixed in close proximity to the glower. In order to avoid unnecessary waste of current, an automatic cut-out is provided in the lamp, which is operated by the glower current, and which interrupts the heater circuit as soon as current passes through the glower. The glower has the further disadvantage that the voltage and current, at or in the neighbourhood of the working temperature, are not in stable equilibrium, an increase of current being accompanied by a fall in potential difference, and consequently a steadying resistance has to be used in series with the glower, as will be explained more fully presently. In Fig. 46 is shown diagrammatically the scheme of the Nernst lamp.

When pressure is first switched on the glower circuit P G M R N is non-conducting, as the glower G is cold, and current can, therefore, only pass through the heater circuit P H C S N. The temperature of the heating coil H is thereby raised and after a time the glower becomes

sufficiently hot to conduct; current now flows round the glower circuit, which includes the magnet coil M and the steadying resistance R. As a result of the energising of the magnet, the spring S is drawn into the dotted position, and the heater circuit broken; S remains in this position until the pressure is switched off, when it returns to the position shown in full in the diagram.

MANUFACTURE.

The Glower.—The glower is composed of a mixture of

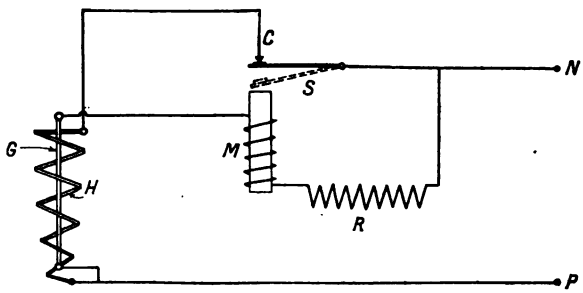


FIG. 46.—Scheme of connections in Nernst lamp.

oxides of the rare earths, which have individually and also when mixed very high melting-points. Various ingredients may be used with equally satisfactory results, the performance of the glower appearing to depend more upon the purity of its components and the method of manufacture than on the actual oxides used. A good mixture, and one formerly (if not still) the standard, is 85 per cent. of zirconia and 15 per cent. of yttria and erbia. Yttria and erbia occur naturally together, and are very similar in chemical properties, their separation being a matter of great difficulty; fortunately, it is unnecessary to effect

this, and the mixed oxides can be used in their naturally occurring proportions without any disadvantage. Ceria and thoria may also be used in the mixture. The oxides must be obtained in a very pure state, and also in an extremely finely divided condition. A good method is to prepare pure solutions of the chlorides, and mix these in the proportions necessary to yield on precipitation the mixed oxides in the right proportions. The solution can be precipitated with ammonia, which produces a gelatinous precipitate of the hydroxides, yielding the oxides on calcination. Other methods may, however, be employed. The calcined oxides are mixed to a stiff paste with gum, gum tragacanth being particularly suitable, and about 5 per cent. being sufficient. This paste is forced by a press through a small die, from which it issues in the form of a continuous and fairly strong thread, which soon dries to a stiff rod. For the larger diameter filaments, a needle is fixed in the centre of the die, so that the filament issues as a tube. These rods have now to be baked to a very high temperature, which is best attained by electrical baking. Very good results may be obtained by baking the rods in an electrical tube-furnace, the tube itself being composed of the same material as the glower. Carbon tubes are not very suitable, as they are liable to lead to the formation of carbides. The Nernst tube furnaces are not very satisfactory from a practical manufacturing point of view, and the writer does not know if they are still in use. Filaments can be baked in the oxyhydrogen flame or by passing them slowly through an arc, or indeed in any way in which a high enough temperature can be obtained without introducing impurities. The baked filaments are cut to the required

length and mounted; the mounts are formed by winding a skein of fine platinum wire tightly round the filament, as shown in Fig. 47 (*a*), and covering the joint with a paste composed of very finely ground and strongly baked (preferably fused) glower material. This powder is mixed with a little solution of the chlorides of the rare earths to a thin paste, which is applied to the joint and then strongly heated to convert the chlorides to oxides; a very firm joint can be made in this way (Fig. 47 (*b*)). Another method is to fuse the end of the glower in an oxyhydrogen flame or arc and insert into the fused globule a fairly thick platinum wire.

The size of the glowers is approximately as follows: 1 ampere, 1 *m/m* diameter, 32 *m/m* long, for 200 volts; 0·25 ampere, 0·4 *m/m* diameter, 24 *m/m* long, for 200 volts. The length is not proportional to the voltage, on account of the drop in volts and the cooling effects at the mounts.

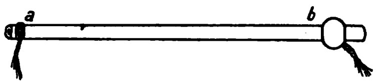


FIG. 47.—Method of forming mounts on Nernst filament.

The Heater.—In the early days of the Nernst lamp it was proposed to make lamps without heaters, which were to be lighted with a match or spirit lamp, and many excellent lamps were made in this way. They had the advantage of cheapness and extreme simplicity, and it seems a mistake that this type of lamp was not more fully developed. But, for some reason, these lamps did not meet the requirements of the market, and electrical heating devices had to be developed, so as to make the lamps self-lighting. The heater of modern Nernst lamps consists of a porcelain rod, on which is wound a spiral of fine platinum

wire. The rods may be squirted in the same way as the filaments from a mixture of china clay and gum, and baked in the usual porcelain kilns. The spiral of platinum is then wound on, and is protected by giving it a coating of kaolin; the rods can be bent to any required shape in a Bunsen flame. The spiral heaters used in the larger lamps may be formed by winding the rods on to a former of the correct shape, the former and rod being kept hot by a blow-pipe flame during winding. The ends of the platinum spiral are secured by nickel wire twisted on to form a mount in the same way as the mounts on the glower are made, the mount being protected by a covering of kaolin.

Steadying Resistance.—The essential requisite of the

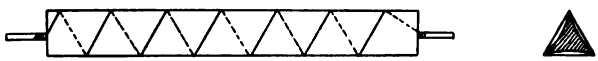


FIG. 48.—Platinum wire steadying resistance.

steadying resistance is that it shall have a high positive temperature coefficient, so that a very small increase in current is accompanied by a great rise in potential difference. Fairly satisfactory resistances can be made by winding fine platinum wire on porcelain formers, as shown in Fig. 48, the formers being so shaped that the wire is in contact with the former in as few places as possible. The wires must be very fine, and for heavy currents many wires must be used in parallel instead of one thick wire; the wire must be of such a diameter that it is just below a red heat when the normal working current is flowing. Iron wire possesses, however, the necessary properties in a much more marked degree than platinum, and iron wire resistances are now universal. The wire must be protected from the

oxidising action of the atmosphere by enclosing it in a bulb, which is either exhausted or filled with hydrogen at a low pressure. These resistances have the form shown in Fig. 49; the fine iron wire is wound into a spiral, and fixed on to a nickel wire frame; the whole is enclosed in a bulb, the air is exhausted and the bulb is then filled with pure dry hydrogen at the desired pressure and sealed. The wire is of such a diameter that the normal current raises it to just below a red heat, and the regulation obtained with many fine wires in parallel is far better than that obtained with a single thick wire These resistances have truly remarkable characteristics, which will be discussed later.

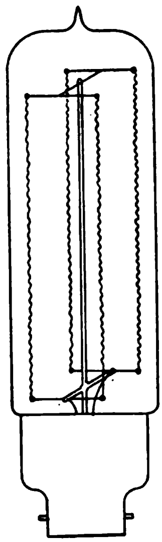


FIG. 49.—Iron wire steadying resistance.

The cut-out does not call for special description. It consists of a small electro-magnet attracting a light spring armature which carries the heater circuit contact. The chief requisites are that it shall absorb as little power as possible, be certain in action, and be silent on alternating current.

The glower, heater, resistance, and cut-out are mounted in a suitable lamp case. The glower and heater are mounted together on a porcelain base, so that they can easily be renewed when either fails, and the resistance is also fixed in such a way that its replacement is easy and can be effected by the user. The cut-out is permanently fixed to the lamp.

PHYSICAL CHARACTERISTICS OF THE NERNST LAMP.

In Figs. 50 and 51 are given typical curves showing the connection between the current flowing through a Nernst

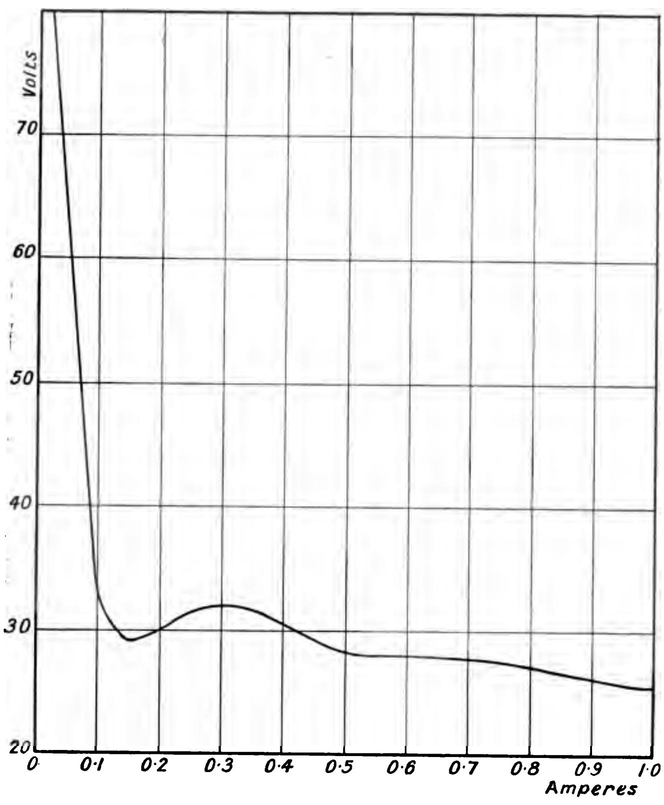


FIG. 50.—P.D.-current curve for Nernst filament.

filament and the potential difference at its terminals. The curve in Fig. 50 is for a very short filament in order to show the full range of current and P.D. values. It will be noticed

that as the current is increased the potential difference at first falls very rapidly, then rises and finally again falls, this last fall continuing until the filament fuses. The curve in Fig. 51 is for a filament of normal length (suitable for a 0·25 ampere 100-volt lamp) and shows on a larger scale the

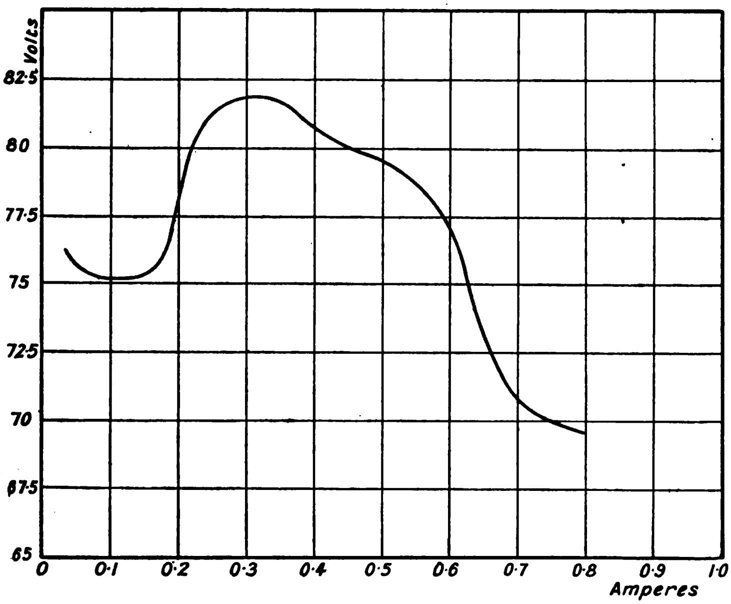


FIG. 51.—P.D.-current curve for Nernst filament.

most important part of the curve, that in the neighbourhood of the normal working current.

From the study of these curves the conditions for stability of the filament current can be determined. Suppose in the first case that the glower is connected direct to a generator of E.M.F., E (Fig. 52) and draw the line E A B C corresponding to this E.M.F. cutting the P.D.-current curve at

A, B and C. As there is no fall of P.D. in external resistance the P.D. at the filament terminals must be equal to E and the current must, therefore, have one of the values O A′, O B′ or O C′ corresponding to the points of intersection A, B and C. Of these three values O B′ is the only possible

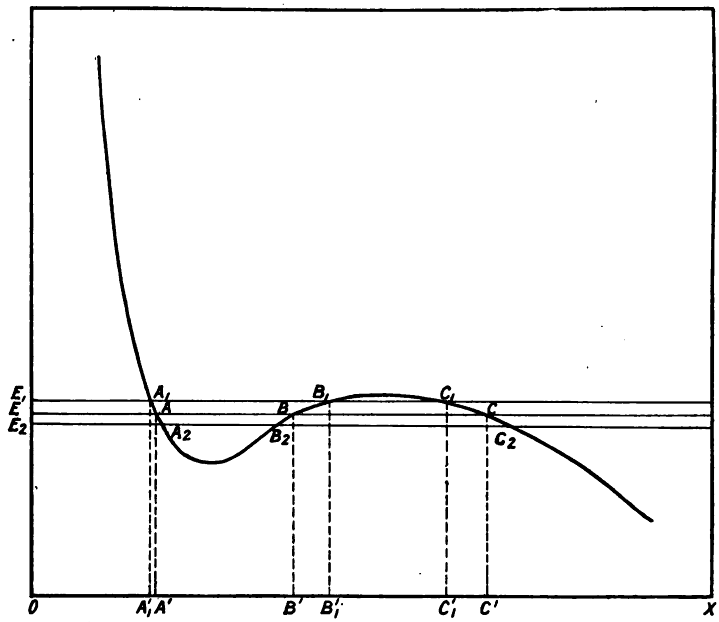


FIG. 52.—Conditions for stability of filament current.

stable value under the given conditions. For, let the E.M.F. rise slightly to the value E_1 and draw the line $E_1 A_1 B_1 C_1$ as before. The new value of the current must be O A'_1, O B'_1 or O C'_1. Now the rise in E.M.F. must occasion an increase in current, since the resistance of the glower is unchanged at the moment the rise takes place, but both

the currents O A'_1 and O C'_1 are less than the original currents O A′ and O C′, and in order that the current should assume these values after the rise in E.M.F. it would be necessary for this rise to produce a fall in the initial current. In the same way it can be seen that a fall in E.M.F. from

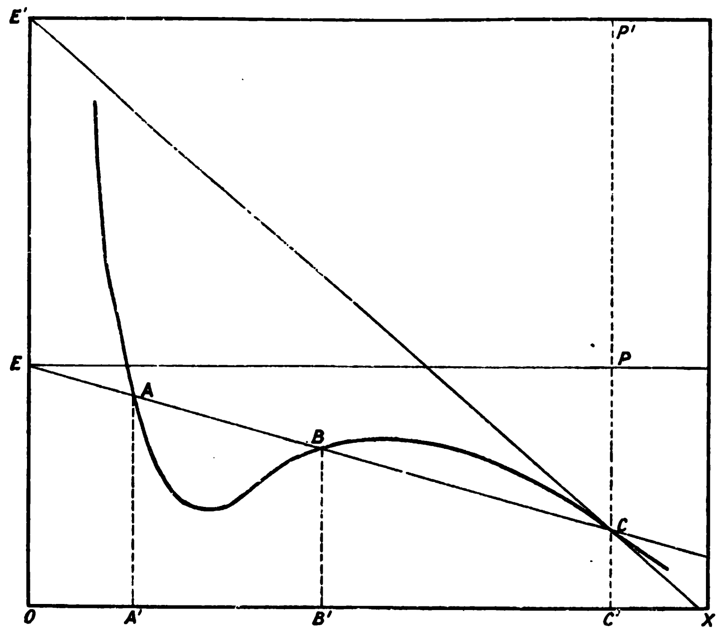


FIG. 53.—Stability of filament current with resistance in series.

E to E_2 cannot occasion the *increase* of current from O A′ to O A'_2 or from O C′ to O C'_2. The inclination of the P.D.-current curve at B is, however, in the right direction; the value of the current corresponding to a higher P.D. after the change being greater, and that corresponding to a lower P.D. smaller, than the initial value of the current.

If a resistance is connected in series with the filament there will be a fall in P.D. in this resistance. Draw the line E P (Fig. 53) as before, corresponding to the generator E.M.F. and plot *downwards* from this line the values of the P.D. drop in the series resistance with different currents, thus obtaining (for a constant resistance) the line E A B C. Exactly the same argument as before will show that the current corresponding to the point of intersection B is again the only stable current under these conditions.

In general, when the *resistance line* E A B C cuts the P.D.-current curve from above (as at B), the condition represented is stable, but when it cuts the P.D.-current curve from below (as at A or C) the position is unstable.[1] It is sometimes erroneously stated that the instability of the Nernst filament is due to its possessing a negative temperature coefficient. A carbon filament possesses a negative temperature coefficient, its resistance being lower when hot than when cold, but is nevertheless stable. The criterion of stability is not the temperature coefficient but the slope of the P.D.-current curve: when a small *rise* in P.D. $d\,V$ is accompanied by a small *rise* in current $d\,A$, *i.e.*, when $\frac{d\,V}{d\,A}$ is positive, the condition is a stable one: when a small *rise* in P.D. is accompanied by a small *fall* in current, *i.e.*, when $\frac{d\,V}{d\,A}$ is negative, the condition is unstable. In order to determine the stability of a circuit containing both filament

[1] The argument is precisely the same as that applied by M. Blondel to explain an exactly similar phenomena in the electric arc, and very fully and lucidly explained by Mrs. Ayrton: *The Electric Arc*, Chapter VIII. The case of the Nernst filament is peculiar as the curve possesses one stable and two unstable regions.

and resistance it is necessary to find the sign of $\frac{d\,V}{d\,A}$ for the combined circuit. This can be done by plotting a curve the ordinates of which are equal to the *sums* of the P.D.'s of filament and resistance; if this curve slopes upwards from left to right the condition is stable, if downwards unstable. A more simple method is to see whether the resistance line cuts the P.D.-current curve from above or not. Thus in Fig. 53, whereas the point of intersection C is unstable when the generator E.M.F. is E, it is stable when the generator E.M.F. is E′, and a resistance is used in series with the filament over which with current O C′ there is a P.D. = P′ C. It will be seen therefore that to obtain all the points on the P.D.-current curve it is necessary to use an E.M.F. very high compared with the actual P.D. between the ends of the filament. For this reason a very short filament was used to obtain the curve in Fig. 50, and even though the normal P.D. between the ends of this filament was only about 32 volts, a generator E.M.F. of 300 volts was necessary in order to obtain the points on the first part of the curve.

The P.D.-current curve is also very interesting in connection with the lowest burning current and the lighting-up temperature of the glower. It is evident from what has preceded that the lowest current at which a given filament will burn steadily depends simply on the E.M.F. available and the resistance in series with the filament. The lowest burning current is determined by the position of B, Fig. 53, and in order that E B may cut the P.D.-current curve from above at a point corresponding to a small current, O E must be great and the angle P E B large. The greater

therefore the potential difference over the external resistance the smaller the value of the lowest burning current. In confirmation of this the following experiment may be described. Three filaments of the same diameter and material were mounted so that the lengths between the mounts were 5 *m/m*, 12·5 *m/m* and 24 *m/m* respectively, and all three were tested on a 200-volt circuit. This was equivalent to testing a filament of fixed length on circuits of different voltages. It was found that the lowest burning currents were 0·015, 0·07 and 0·10 amperes respectively. The normal working current for these filaments was 0·5 amperes. Since the P.D.-current curve rises rapidly as the current approaches zero, the E.M.F. necessary to maintain a very small current steadily flowing is very large: if the curve eventually becomes parallel to the axis of P.D. there is a lower limit below which no current can be maintained, however high the available E.M.F.

Consider now the question of the lighting-up temperature. When a Nernst lamp is lighted the filament is heated by external means until it attains a certain temperature at which it will have a definite resistance g_1. Let the external E.M.F. be E, Fig. 54, and the resistance in series with the filament r. Then a current will flow equal to $\frac{E}{r + g_1}$, which will itself heat the filament to a higher temperature at which it will have a resistance less than g_1. The current will consequently increase until a steady condition is reached, at which the filament has a resistance g_2. The steady current flowing will now be equal to $\frac{E}{r + g_2}$. Let this current be represented on the diagram by O A′. Draw E A

as before such that *tan* P E A = r, and O A such that *tan* X O A = g_2. The point of intersection A of E A and O A determines the position of A′. Since the filament is hotter than it would be if heated solely by the current O A′ its resistance must be lower than it would be as a result of the

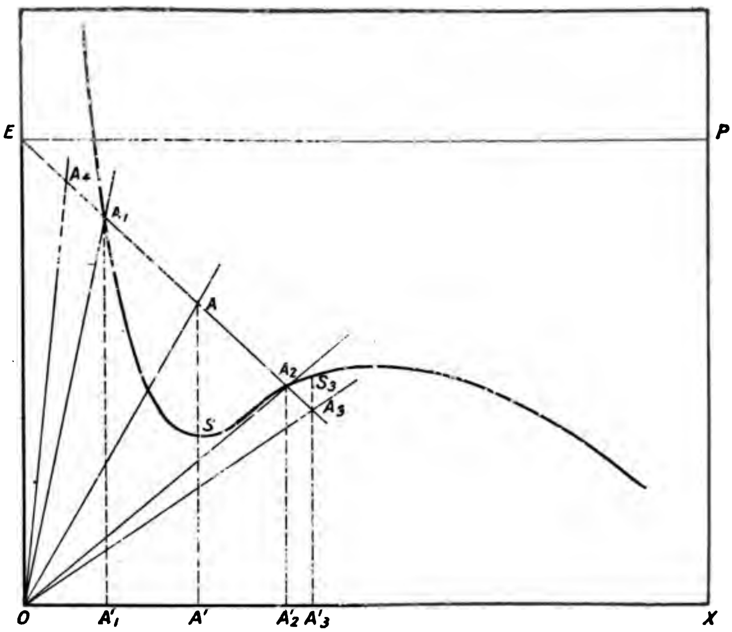


FIG. 54.—Conditions for lighting-up of Nernst filament.

electrical heating alone. The P.D. at its ends must therefore be less than that required to maintain the current O A′ without external heating. But this P.D. is S A′. Hence A A′ the actual P.D. at the ends of the filament must be less than S A′, *or the point A must lie below the P.D.-current curve.* The position shown is therefore clearly impossible:

under these conditions the current would go on increasing until it finally attained a steady value such as O A'_3 for which the condition that A_3 A'_3 must be less than S_3 A'_3 is satisfied. If the resistance line E A cuts the P.D.-current curve at A_1 and A_2 it will be seen that A can lie anywhere on E A except between A_1 and A_2. The current which flows through the filament whilst the external heating is still applied must be therefore either *less* than O A'_1, or *greater* than O A'_2, and the resistance of the filament (due to the electrical and external heating) must be either *greater* than *tan* X O A_1, or *less* than *tan* X O A_2. Suppose the resistance is greater than *tan* X O A_1, say equal to *tan* X O A_4, and let the external source of heat be now removed. As the filament cools the current will fall in a manner determined by the movement of A_4 along A_4 E. As A_4 in moving along A_4 E never meets the P.D.-current curve a value of the current is never reached at which the filament can burn under the given conditions of E.M.F. and resistance, since for all such values A_4 must lie on the P.D.-current curve. As a result the current falls to zero and the lamp goes out. When however the resistance is less than *tan* X O A_2, say equal to *tan* X O A_3, and the external heating is removed, A_3 in moving along A_3 E eventually comes to the P.D.-current curve at A_2, and at the current corresponding to this position (O A'_2) the filament will continue steadily burning. Hence in order that the filament may light up, the initial current must have a value greater than O A'_2, and it has already been shown it will attain such a value provided it attains a value greater than O A'_1. The resistance of the filament due to the external heating combined with the heating produced by the starting current as it grows must therefore

fall to a value less than *tan* X O A_1, and in the limiting case we may say that the resistance due to the external heating *alone* must be less than *tan* X O A_1. The lighting-up temperature is therefore determined by the position of A_1, the *first* point of intersection of the resistance line and the

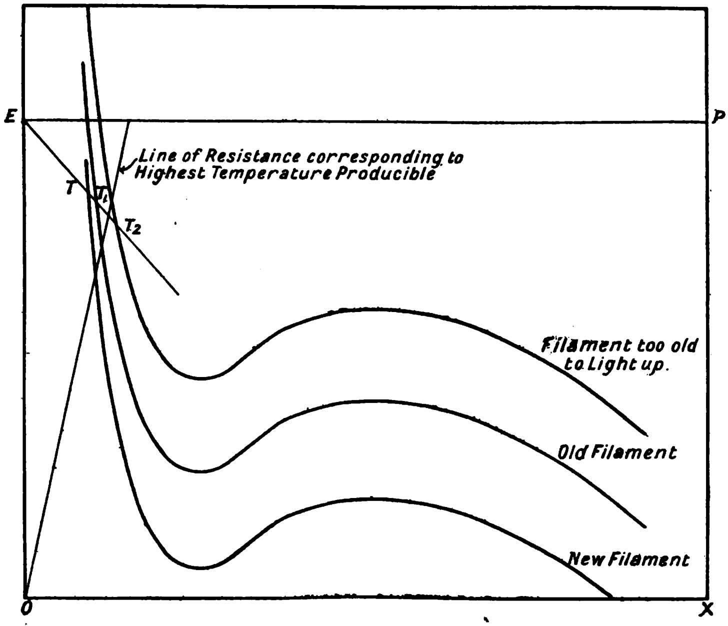


FIG. 55.—Ageing of Nernst filament and lighting-up temperature.

P.D.-current curve. This depends upon the P.D.-current curve, the E.M.F. and the external resistance. There is therefore no such thing as an absolute lighting-up temperature for a given filament: it will be seen at once that the higher the applied E.M.F. and the lower the external resistance, the lower the temperature at which the filament starts up. For given external conditions the lower the

resistance of the filament (or more accurately the lower the P.D.-current curve) the lower the lighting-up temperature. This explains a phenomenon often observed with Nernst lamps that, as the lamps grow old, the time taken to light up increases until eventually the filament will not light up at all. As the filament ages its resistance increases, and the P.D.-current curve rises bodily, the point T (Fig. 55) moving from left to right along the axis of current until eventually it corresponds to a temperature higher than that which the heater can produce, as is shown diagrammatically in the figure.

TABLE XIV.

Filament Resistance at 0·4 amperes.	Thermocouple Reading at lighting-up Temperature.
400	37
425	40
440	50
560	Greater than 57

Some experiments made by the writer which confirm these conclusions may be quoted. Four filaments of the same diameter and material were made of different lengths so as to have different resistances. A small electrical furnace was constructed in which the filament to be tested could be completely enclosed, and a thermocouple was inserted in this furnace as close as possible to the filament. The filament was connected in series with a fixed resistance on a supply of definite E.M.F., and the furnace slowly heated up. Readings of the thermocouple indications were taken every two minutes until the filament lighted up; the lighting-up could be quite definitely determined by watching an ammeter connected in series with the filament; the

current at first increases very slowly until a certain current (corresponding to O A'_1, Fig. 54) is flowing, when there is a sudden increase (to a value corresponding to O A'_3). The

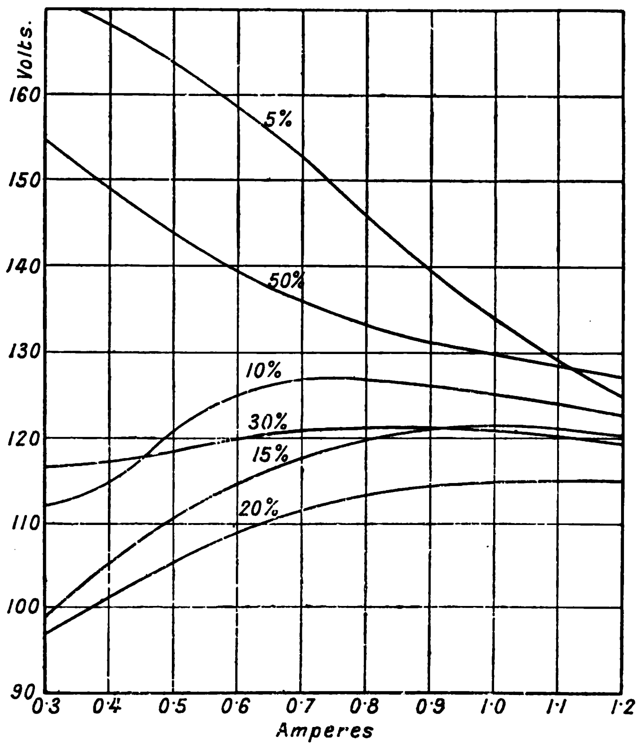


FIG. 56.—P.D.-current curves for Nernst filaments of different compositions.

thermocouple reading at the moment this current rush occurs was taken as a measure of the lighting-up temperature. The results are given in Table XIV. The last filament would not light up at all at the maximum temperature attainable in the furnace.

The P.D.-current curve varies in shape according to the conditions under which the glowers are run. Mr. A. J. Wurts published in 1901[1] some interesting P.D.-current curves for filaments run in vacuo, in air, and in several different gases. The curve also varies with the composition of the glower; the writer obtained some curves for glowers of six different compositions in which the percentage of yttria varied from 5 to 50. As these or similar curves have not been published previously they are reproduced in Fig. 56. To the writer's best knowledge all the published P.D.-current curves give only that part of the curve in the neighbourhood of the working current, the full curve in Fig. 50 being the first to show the characteristics down to very low values of the current, which is needed, as has been shown, for the proper interpretation of all the phenomena of the filament.

Intrinsic Brightness.—The intrinsic brightness of the Nernst filament run at various watts per candle is shown by the figures in Table XV.

TABLE XV.

Watts per Candle.	Candle-power per sq. m/m Surface.
1·25	4·73
1·50	3·62
1·75	2·82
2·00	2·18

The average intrinsic brightness varies slightly with the length of the filament, as the mounts produce considerable cooling of the filament ends.

[1] *The Electrical Review*, New York, Aug. 31, 1901.

Polarity.—That the conduction in Nernst filaments is essentially electrolytic in nature is shown by the fact that even a few minutes running on direct current is sufficient to give the filament properties indicating the existence of a definite polarity, and if the current is now reversed the filament in all probability breaks at the original positive end. This breakage does not always occur, and is less liable to occur the shorter the period for which the filament has been run before reversal. It will usually be found that if the filament survives the first few hours' running after reversal its polarity appears to be reversed and it continues to burn quite satisfactorily. Nevertheless it is obvious that the greatest care must be taken to avoid reversal, and lamps must always be connected up with the correct polarity as marked on the lamp by the manufacturers. For similar reasons direct current filaments must not be used on alternating current circuits; the reverse process is less objectionable. At one time different compositions were used for alternating and direct current filaments; the writer is not aware if this is still the case. It is, however, quite possible with proper precautions to make filaments of the same composition equally satisfactorily for direct or alternating current. The polarity of the filament is further evidenced by the greater heating which always occurs at the positive mount, and the greater drop of potential at this mount.

The Series Resistance.—It has already been shown that it is possible to burn a Nernst filament without any resistance in series though under very unstable conditions. In discussing the P.D.-current curves it has been assumed that a constant resistance, *i.e.*, a resistance which remained of the

same value for all values of the current, was used in series with the glower. It is easy to see, however, that such a resistance is unsuitable; take for example the P.D.-current curve in Fig. 57 for a filament in series with a resistance equal to *tan* P E A. If the E.M.F. rises above E_1, the filament will fuse, and if it falls below E_2 the filament will go

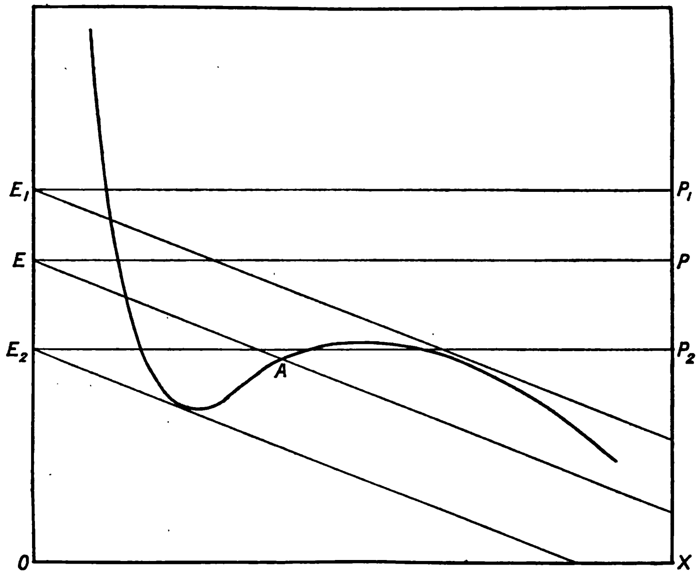


FIG. 57.—Stability of Nernst filament with constant series resistance.

out. The permissible variations in supply voltage under these conditions are accordingly very small, and, moreover, the alterations in current even when the voltage does not vary beyond these limits is excessive. To avoid this, it is necessary that the resistance line E A should be as nearly vertical as possible at the working current. This could be secured by using a very high resistance and a very high

E.M.F., but such a course is obviously undesirable, as the power wasted in the resistance would then be very great. The line E A can be made nearly vertical at the working current in another way by using a resistance having a very high temperature coefficient. A very small increase in the current will then, by slightly raising the temperature of the resistance wire, cause a great rise in the potential difference between its ends. The iron resistances, and to a

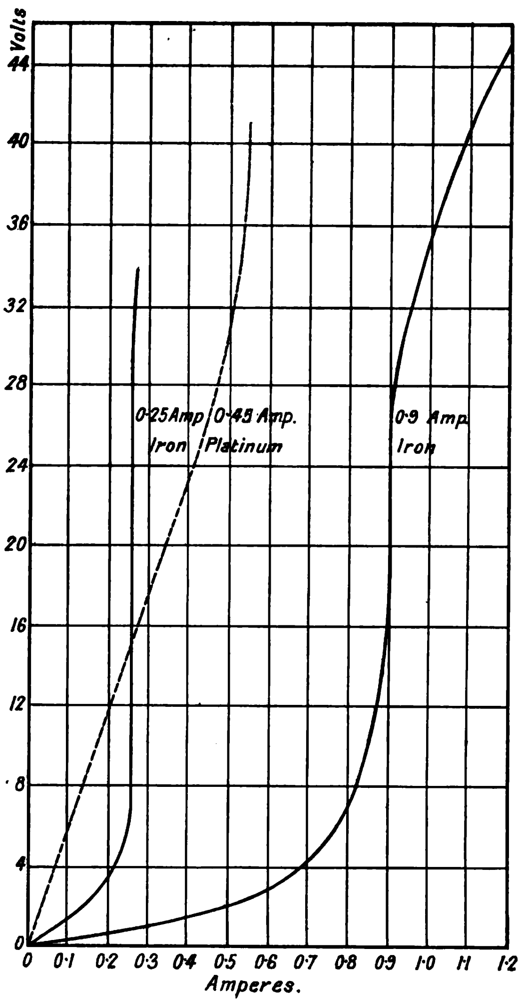


FIG. 58.—P.D.-current curves for iron and platinum series resistances.

lesser extent the platinum resistances, already described, possess this property to a remarkable degree in the neighbourhood of a red heat. In Fig. 58 are shown the P.D.-current curves for two iron resistances, and by way of comparison a similar curve (dotted) for a platinum resistance. It will be seen that with the iron wires the P.D. rises at first slowly, then more rapidly, and then so quickly that the curve

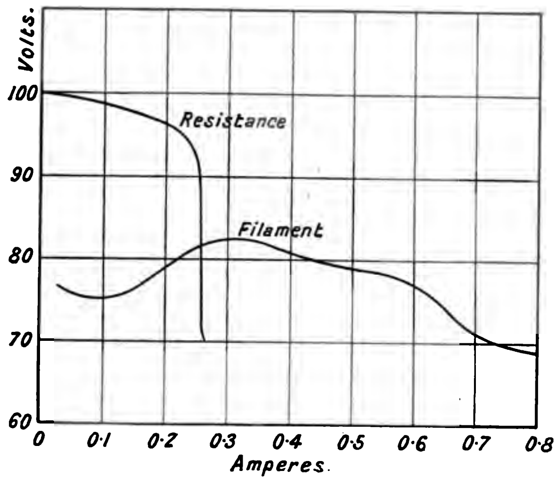


FIG. 59.—Nernst filament in series with iron steadying resistance.

becomes almost vertical; finally the P.D. rises less rapidly, the curve bending over towards the horizontal. The sudden sharp rise is particularly interesting; practically for a certain value of the current it will be seen that the P.D. may have any value over a considerable range. This value of the current is the correct working value for the resistance, and may be called the regulating current. The conditions for a filament in series with such a resistance are shown in

Fig. 59. It will be seen that the value of the current through the filament is practically determined by the resistance, and that a very considerable rise or fall of the supply voltage would produce only a very slight alteration in the current. The analysis already given of the consequences of the shape of the filament P.D.-current curve applies equally well when a series resistance of this type is used, though for simplicity it was assumed in discussing these consequences that a constant resistance was in series with the filament.

The value of the regulating current and the sharpness of the regulation of an iron resistance depend on the size of wire used, the pressure of gas in the bulb, and the way in which the wire is fixed. It has already been mentioned that the regulation is sharper the finer the iron wire, and for this reason when the current is great two or more wires in parallel are preferable to a single wire. The regulation is also sharper the better the vacuum in the bulb, but the better the vacuum the lower the current at which the wire becomes red hot; some compromise must, therefore, be made, sufficient pressure of gas being used to enable wire of a reasonable diameter to be employed. A pressure of 12 to 14 c.m. of mercury is very satisfactory. The wire should also be fixed as freely as possible; it is generally wound in a very open spiral, as shown in Fig. 49, p. 144. The more open this spiral the sharper the regulation, but here again a compromise must be made in order to get the necessary length of wire into the bulb. The small resistances used in the smaller lamps are always less satisfactory on account of the necessary crowding of the wire. The nearness of the wire to the bulb and the position of the

bulb in the lamp also affect the regulating current; this can be readily understood since the regulation takes place at a particular temperature. Anything, therefore, which affects the temperature of the bulb will affect the value of the regulating current.

The remarkable characteristics of these resistances suggest their application to other uses. Their use in series with standard incandescent lamps has already been mentioned (p. 133), and they may well be employed in other cases in which a constant current is required. Similar resistances have recently been adapted for use in series with flame arcs; the writer suggested their use with arc lamps in 1903.[1] It may be mentioned that though these series resistances are classified according to current and voltage, *e.g.*, 0·5 amps. 15 volts, the value of the voltage is obviously to a certain extent only nominal.

Potential Difference and Candle-power.

The Nernst lamp consisting of a combination of the filament and the series resistance, its behaviour under varying conditions of voltage depends naturally on the characteristics of these two components. It has been thought better, therefore, to discuss each of these separately, but there remains the question of the variation of candle-power with variation of voltage, which it is better to consider for the lamp as a whole. Variation of candle-power depends on variation of temperature, and this must be always regarded in incandescent lamps as directly dependent on

[1] *Journal of the Institution of Electrical Engineers*, Vol. XXXII., p. 532.

the current and only indirectly dependent on the voltage. There will be a great change in the candle-power for a given change in the voltage when this voltage change produces a great change in the current. Since, therefore, the regulating resistance keeps the current through the Nernst lamp practically constant over a large voltage range the

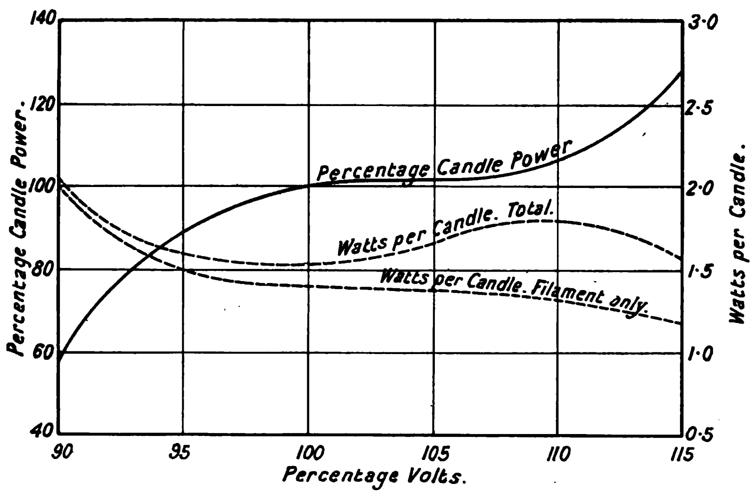


FIG. 60.—Candle-power and watts per candle variations with Nernst lamp.

candle-power will also vary very little over this range; above and below this range the variation will be more rapid. These conclusions are fully borne out by the curves in Fig. 60, showing the variation of candle-power and watts per candle with voltage. These may be advantageously compared with the similar curves for carbon filaments on p. 112.

The watts per candle will vary somewhat differently to

the candle-power, since the watts absorbed by the non-light-giving resistance have to be taken into account. In some cases these may increase so rapidly that there is an actual increase in the total watts per candle when the lamp is overrun, as shown in Fig. 60, although, of course, when the watts absorbed by the filament only are considered, there is a steady fall in watts per candle as the voltage is increased. By overrunning a carbon filament lamp one

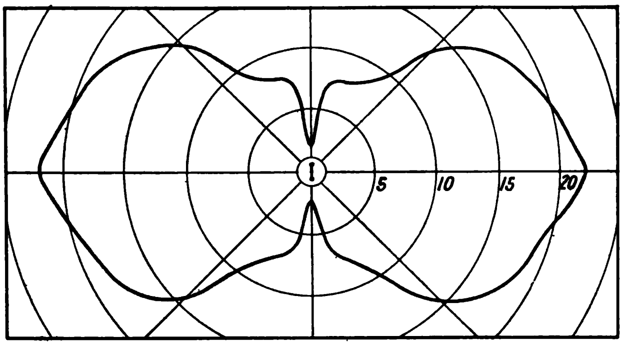


FIG. 61.—Horizontal distribution curve. Nernst lamp with straight horizontal filament.

obtains always a worse life at a better efficiency; by overrunning a Nernst lamp it is possible that the worse life is obtained without any advantage in efficiency.

DISTRIBUTION OF LIGHT.

In Fig. 61 is given the horizontal distribution curve for a Nernst lamp with straight horizontal filament, and in Fig. 62 the vertical distribution curves for the same lamp, the full curve showing the distribution in the plane at right angles to the filament, and the dotted curve that in the plane of the filament. There is naturally a very marked

difference between these two curves. A method for obtaining a mean vertical distribution curve for a lamp of this type has been given in Chapter IV., p. 78. The exceedingly low values of the candle-power in the two directions along the actual axis of the filament are due to the presence of the mounts and supports at each end. In Fig. 63 is given the vertical distribution curve for a lamp with straight vertical filament; the normal horizontal distribution curve for a lamp of this type may be regarded as a true circle.

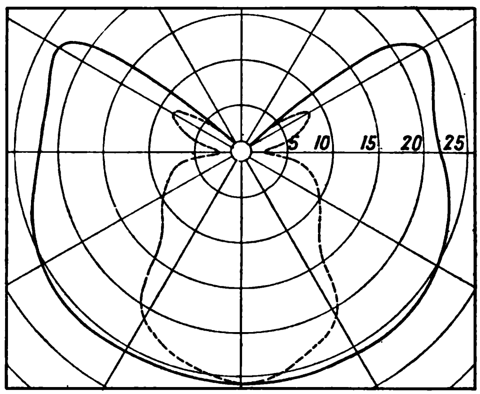


FIG. 62.—Vertical distribution curves. Nernst lamp with straight horizontal filament.
Full curve, in plane at right angles to filament.
Dotted curve, in plane of filament.

The curves are all for lamps without globes; a clear globe modifies the shape of the curve but little; a frosted globe smooths out the more marked inequalities. When the heater surrounds the filament (as in the case of the lamp in Fig. 63), a certain amount of the light amounting to from 2 per cent. to 5 per cent. is cut off, and the light in certain directions is modified by the heater shadows.

RATING AND LIFE.

Nernst lamps are rated by the manufacturer according to voltage and current, the candle-power varying according

to the voltage. Thus lamps are made for 0·25 amperes and say 200 and 220 volts; the 200-volt lamp will be 32 candle-power and the 220-volt lamp 35 candle-power. This rating by current is to a certain extent necessitated by the fact that resistances and burners have to be sold separately, but apart from this it is in many ways preferable to the candle-power rating. If all lamps were rated in this way the consumer would know what he is going to pay

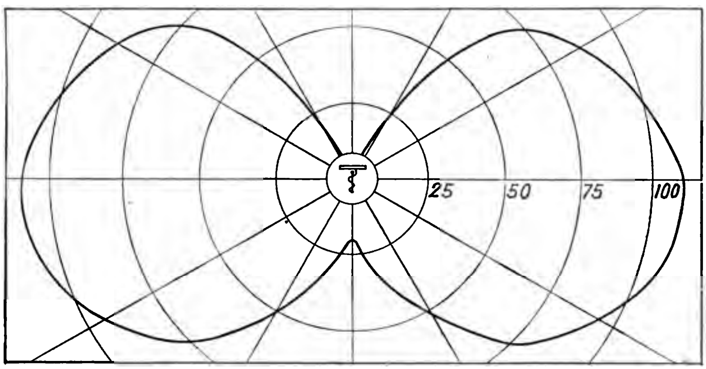


FIG. 63.—Vertical distribution curve. Nernst lamp with straight vertical filament.

for energy for burning each lamp, and he could tell approximately himself which lamp suits him best, lasts longest, or gives him the best return in illumination for the money spent. But when he buys two lamps, each of 16 candle-power, he has no idea how much current each is taking, and it is a very difficult, or even impossible, matter for him to find out which is the most economical from his lighting bills.

The Nernst lamp is at present made in various sizes; the standard filaments take 0·25, 0·5, and 1·0 amperes

respectively. The quarter and half-ampere filaments are mounted in lamps that can be fitted into the ordinary lamp-holders as used for carbon filament lamps; the one-ampere filaments are mounted in lamps which have to be separately suspended in the same way as arc lamps, and

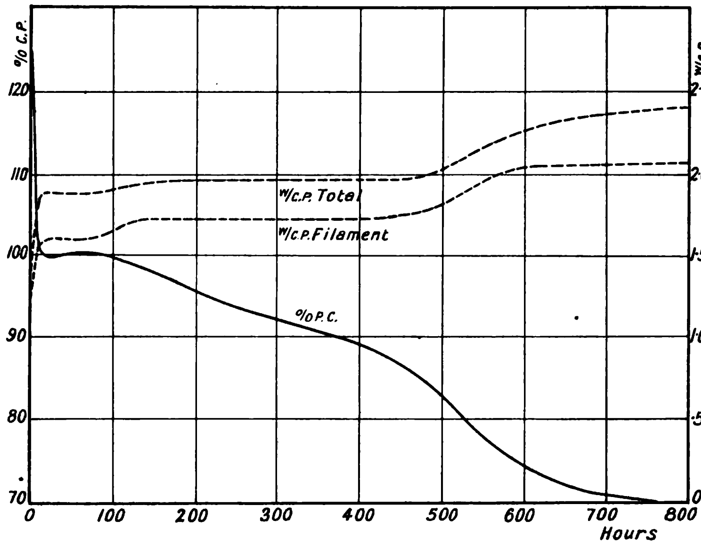


FIG. 64.—Life test curve for 200-volt one-ampere direct-current Nernst lamps.

the half-ampere filaments can also be obtained mounted for this type of lamp. Multiple filament lamps are also made having three half-ampere or three one-ampere burners. The candle-power varies, as already stated, with the voltage, and may be calculated approximately on the basis of a power consumption of 1·5 watts per candle for the larger and 1·75 watts per candle for the smaller lamps.

The life of Nernst lamps is very variable, so much so

that it is possibly better to define their useful life as the life till failure, rather than the life till the candle-power has fallen 20 per cent. Some lamps will fail after a few hours, others may last only 30 to 50 hours, and others again run for 500 to 1,000 hours. Roughly, the average life may be

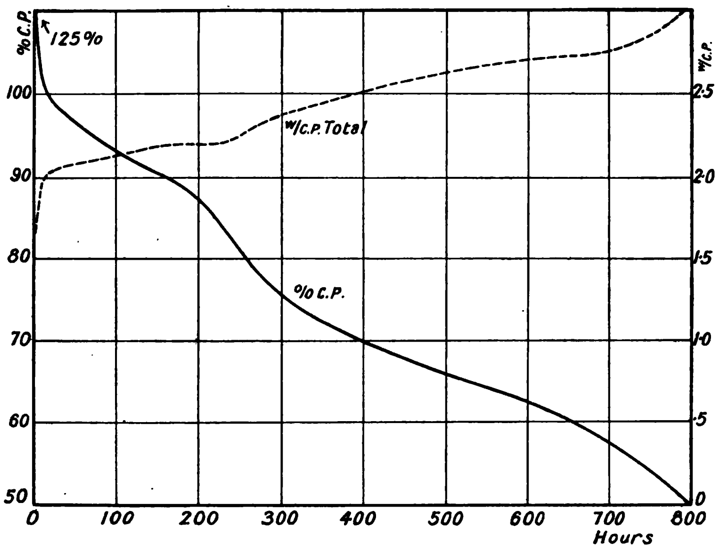


FIG. 65.—Life test curve for 200-volt one-ampere alternating-current Nernst lamps.

taken as about 500 hours for direct-current lamps and 300 hours for alternating-current lamps.

In Figs. 64 and 65 are given typical life test curves for direct and alternating 200-volt one-ampere lamps. It is generally characteristic of Nernst lamps that there is a very marked fall in candle-power during the first few hours' burning, as is shown in these curves, but this characteristic is not always present. On account of this the

percentage candle-powers in Figs. 64 and 65 have been calculated in reference to the actual candle-power after 20 hours' use, instead of in reference to the true initial candle-power. It will be seen that there is a continuous falling off in candle-power during life, which becomes steeper towards the end of the life. The average life (till failure) for the five direct-current lamps (Fig. 64) was 750 hours, and for the five alternating lamps (Fig. 65) 700 hours, but the corresponding useful lives (20 per cent. fall), it will be seen, were only 520 and 260 hours respectively.

On account of the uncertainty in life, it is difficult to give a true estimate of the cost of lighting with Nernst lamps. Firstly, a decision has to be made as to whether the life till failure or the "useful" life will be taken as the basis of comparison; secondly, the question of the renewal of other parts than the burner (*i.e.*, filament and heater) has to be considered; and finally, the costs of maintenance and depreciation, items by no means negligible with Nernst lamps, have to be taken into account. It seems better for the purpose of this book, however, to neglect these last items, as charges of this sort vary immensely according to the precise conditions of the installation. Thus Nernst lamps used for outdoor street lighting will cost very much more for upkeep, and will involve much heavier depreciation charges, than when used for interior lighting.

As a basis for the calculation of the lighting cost, independently of these charges, we may take the curves in Figs. 64 and 65 and work out the cost, firstly, when the lamps are run only for the period of their useful life, and secondly, when they are run till failure. From these curves we get the following data :—

DIRECT-CURRENT LAMPS.

Useful life, 520 hours at 1·9 watts per candle.
Life till failure, 750 hours at 2·1 watts per candle.
Life of resistance, say, 1,000 hours.

ALTERNATING-CURRENT LAMPS.

Useful life, 260 hours at 2·2 watts per candle.
Life till failure, 700 hours at 2·4 watts per candle.
Life of resistance, say, 1,000 hours.

We may take the following renewal costs as a basis for calculation :—

	Burner.	Resistance.
¼ ampere	12*d.*	6*d.*
½ ,,	16*d.*	8*d.*
1 ,,	20*d.*	8*d.*

On these assumptions Table XVI. has been worked out showing the cost per 1,000 candle-hours, with energy at various prices per unit. If the figures in this table are examined closely it will be seen that so far as the direct-current lamps are concerned it is practically immaterial whether the lamps are run till they fail or whether they are replaced after the candle-power has fallen 20 per cent., but with the alternating-current lamps it is more economical in all but a few cases (those of the high candle-power lamps when the cost per unit is high) to run the lamps till failure. It is a fairly safe general rule, therefore, to run Nernst lamps until they fail, and this conclusion is supported by the fact, already mentioned, that lamps differ so much in their individual behaviour that any estimate of the cost of lighting can only be regarded as approximate.

TABLE XVI.

TOTAL COST OF LIGHTING PER 1,000 CANDLE-HOURS. NERNST LAMPS.

Cost per B.O.T. Unit.		1d.	2d.	3d.	4d.	5d.	6d.	7d.	8d.
		d.	d.	d.	d.	d.	d.	d.	d.
Direct-current lamps run till 20 per cent. C.P. fall.	100 V. ¼ ampere	4·1	6·0	7·9	9·8	11·7	13·6	15·5	17·4
	100 V. ½ "	3·4	5·3	7·2	9·1	11·0	12·9	14·8	16·7
	100 V. 1 "	2·8	4·7	6·6	8·5	10·4	12·3	14·2	16·1
	200 V. ¼ "	3·0	4·9	6·8	8·7	10·6	12·5	14·4	16·3
	200 V. ½ "	2·6	4·5	6·4	8·3	10·2	12·1	14·0	15·9
	200 V. 1 "	2·3	4·2	6·1	8·0	9·9	11·8	13·7	15·6
Direct-current lamps run till failure.	100 V. ¼ ampere	3·9	6·0	8·1	10·2	12·3	14·4	16·5	18·6
	100 V. ½ "	3·3	5·4	7·5	9·6	11·7	13·8	15·9	18·0
	100 V. 1 "	2·8	4·9	7·0	9·1	11·2	13·3	15·4	17·5
	200 V. ¼ "	3·0	5·1	7·2	9·3	11·4	13·5	15·6	17·7
	200 V. ½ "	2·7	4·8	6·9	9·0	11·1	13·2	15·3	17·4
	200 V. 1 "	2·5	4·6	6·7	8·8	10·9	13·0	15·1	17·2
Alternating - current lamps run till 20 per cent. C.P. fall.	100 V. ¼ ampere	6·7	8·9	11·1	13·3	15·5	17·7	19·9	22·1
	100 V. ½ "	5·2	7·4	9·6	11·8	14·0	16·2	18·4	20·6
	100 V. 1 "	4·1	6·3	8·5	10·7	12·9	15·1	17·3	19·5
	200 V. ¼ "	4·5	6·7	8·9	11·1	13·3	15·5	17·7	19·9
	200 V. ½ "	3·7	5·9	8·1	10·3	12·5	14·7	16·9	19·1
	200 V. 1 "	3·1	5·3	7·5	9·7	11·9	14·1	16·3	18·5
Alternating - current lamps run till failure.	100 V. ¼ ampere	4·6	7·0	9·4	11·8	14·2	16·6	19·0	21·4
	100 V. ½ "	3·9	6·3	8·7	11·1	13·5	15·9	18·3	20·7
	100 V. 1 "	3·3	5·7	8·1	10·5	12·9	15·3	17·7	20·1
	200 V. ¼ "	3·5	5·9	8·3	10·7	13·1	15·5	17·9	20·3
	200 V. ½ "	3·1	5·5	7·9	10·3	12·7	15·1	17·5	19·9
	200 V. 1 "	2·8	5·2	7·6	10·0	12·4	14·8	17·2	19·6

CAUSES OF FAILURE.

It must be remembered that there are several possible causes of failure in Nernst lamps, and also that both the filament and resistance alter with life, so that it is hardly to be expected that the results of life tests should be so uniform as with carbon-filament lamps. The filament

itself always rises in resistance as it gets older, the chief part of this rise being at the mounts. The drop of volts at the positive mount, which is always higher than that at the negative mount, especially tends to rise, and failure very frequently occurs at this mount in consequence of over-heating. The life of the filament is to a very large extent controlled by the amount of platinum put into the mounts; the more platinum used the cooler the mount and the longer the life of the filament. It is in fact possible to predetermine the average life with fair accuracy in this way. The filament also becomes crystalline and much more transparent as it grows older, the crystallisation beginning at the negative mount and gradually spreading along the filament. Under these conditions the filament is a worse radiator; certain impurities increase this effect in a marked manner, the writer having made filaments which, after a few hours' running, gave practically no light for over half their length, starting from the negative mount. The iron resistances are also liable to fail or to alter in the value of their regulating current and the sharpness of their regulation, thus causing failure of the filament. Filaments and resistances must of course be carefully matched; if filaments fail frequently in a particular lamp the fault lies very probably with the regulating resistance, which either does not regulate sharply enough, or regulates at too high a current. Overrunning, or using the lamp on a circuit the voltage of which is normally too high, is more severe on the resistance than on the filament, since the extra voltage is absorbed by the resistance which is consequently continuously running at too high a temperature. The resistance should normally absorb only a few volts,

about 15, so that there is plenty of elasticity towards rise of voltage, fall of voltage being naturally less injurious. For this reason, when the circuit on which the lamps are to be used is known to be normally overrun the sum of the marked voltage on resistance and glower should be greater than the nominal voltage of the circuit. For example, a 190-volt or 195-volt glower should be used in series with a 15-volt resistance for a circuit of (nominal) 200 volts instead of an 185-volt glower.

Another cause of filament failure is the cut-out. Sometimes this gets out of order and does not operate, thus allowing the heater to remain in circuit. In addition to the waste of current, the over-heating of the glower then soon causes failure, or the heater itself may fail. A somewhat similar defect occasionally met with is the following. The heater circuit remains normally broken, but with a slight fall in voltage the filament current drops to a value below that necessary to hold off the cut-out armature; this may be due to the cut-out not operating at a low enough current or to faulty regulation of the filament current. This defect is difficult to detect, but may be suspected if a particular lamp gives bad results with different glowers and resistances. The heaters rarely fail unless due to defective cutting out; failure to light up is not due to defective heaters as a rule, but, as pointed out on p. 155, to ageing of the filament.

Considering the complexity of the Nernst lamp, the number of details in connection with which failure may occur or difficulties arise, and the fact that the lamp does not give light immediately it is switched on, it is not surprising that its use has not become very general. It is

true that the mechanism is less complicated and requires less attention than that of an arc lamp, but it must be remembered that an arc represents a much larger light source, and expense which may be economical in connection with such a source may no longer be justified with the smaller Nernst lamp. In addition, the arc consumes less energy per candle-hour and thus leaves a bigger margin for maintenance expenses. At first it was hoped that the Nernst lamp would effectively displace the carbon-filament lamp, but this it has quite failed to do. It would seem, however, that there should exist a distinct field for the use of the lamp where light units of about 100 candle-power are required, as for example in the lighting of large interiors or of side streets. To a limited extent the Nernst lamp has occupied this field, but it is very questionable whether it will be able to maintain the position long against the competition of the more efficient and less complicated metal filament lamps; possibly its suitability for high voltages and the lower cost of renewals may enable it to withstand this competition for some time, but eventually, unless radically improved, it would seem that it must inevitably yield.

CHAPTER VII

METALLIC-FILAMENT LAMPS

INCANDESCENT electric lamps with metallic filaments are older than carbon-filament lamps. As long ago as 1840 lamps were constructed with filaments of platinum, and for thirty years after that date various attempts were made to construct a practical lamp, using either platinum or iridium wires for the filaments, the only two metals at all suitable which were obtainable at the time. None of these attempts met with any commercial success, and the use of metals was finally abandoned in favour of carbon by the experimenters who developed the carbon-filament lamp in 1878—1880. The success attained with carbon caused all consideration of metallic filaments to be put on one side for nearly twenty years. The introduction of the Nernst lamp appears to have then stimulated research afresh, and many inventors turned their attention to the metals, to find the field greatly widened by the chemical progress which had been made in the meantime. Instead of only two possible metals to work with, there were now numbers known with sufficiently high melting points to suggest great possibilities. After much painstaking effort and laborious work, carried out by inventors who deserve the highest possible praise for both their ingenuity and their perseverance, three commercial metallic-filament lamps have been evolved which have entirely altered the outlook for the future of the electric lighting industry. It is

possible that these may prove to be only the forerunners of further improvements; rumours of fresh developments are of almost weekly occurrence, and it is difficult to say at the moment what is likely to be the course of events during the next few years. Up to the present none of the rumoured improvements have given any evidence of being advanced beyond the laboratory stage, and many do not appear even to have reached that stage, so in the present chapter only those lamps will be described which can claim to have been proved commercial, namely the osmium, tantalum, and tungsten (Wolfram or Osram) lamps. For reasons which will be obvious, it is impossible to give details of the methods of manufacture or the performance of these lamps with anything like the same fulness as for carbon-filament or Nernst lamps. The methods of manufacture are naturally being kept more or less secret; nor are they to any extent stereotyped: all that will be possible here will be to describe the salient features as revealed by the patents and other published matter. As regards the performance, it is as yet too early to do more than give some idea of the results so far attained, and the reader must remember that with a lamp in the first years of its production these results improve from day to day, and that finality cannot be expected for some time to come, even with the remarkably rapid development which nowadays accompanies any new invention.

THE OSMIUM LAMP.

This lamp is the invention of Dr. Auer von Welsbach, and the earliest patents[1] relating to it were taken out in

[1] Reference throughout the chapter is to the English patents.

1898. The earliest reports in reference to the osmium lamp appeared in the technical press in 1901, but the lamp does not appear to have been manufactured commercially until 1903, and it was not until 1905 [1] that it was introduced into this country by the General Electric Company.

Manufacture.— The method of manufacture may be gleaned from the patents, and from a paper read by Dr. Fritz Blau before the Elektrotechnisher Verein in 1905.[2] The process first tried was that of flashing platinum wire in an atmosphere of osmium tetroxide (which is volatile).[3] By subsequently incandescing the alloy in vacuo the platinum can be evaporated off, but it was not found possible to produce sufficiently thin filaments in this way. Finally the method adopted was that of pressing finely-divided osmium, mixed with an organic binding agent, through small diamond or sapphire dies.[4] The thread thus formed is carbonised, and the carbon is then driven off by incandescing the filament in an atmosphere of steam and hydrogen. The filaments have to be raised to a very high temperature in order to "sinter" together the osmium particles into a practically homogeneous filament. Sintering may be described as a sort of modified welding process: the metal does not fuse, but the particles raised almost to their melting point bake together and bind very firmly; as a matter of fact exactly the same phenomenon occurs with carbon filaments, which after the first stages of baking are

[1] See *The Electrician*, Vol. LV., p. 141, May 12, 1905.

[2] Translated (abridged) in *The Electrician*, Vol. LIV., p. 799, March 3, 1905.

[3] Patent No. 1,538, 1898.

[4] Patent No. 17,580, 1898.

highly porous, but become dense and homogeneous on further raising their temperature. The osmium filaments are mounted in bulbs in the same way as carbon filaments, the mount being made by fixing together by means of an arc the end of the osmium filament and the leading in wire.

Performance.—The osmium filaments are very brittle when cold, and this led to heavy breakage in transit, which materially affected the success of the lamp. At the working temperature the filaments are soft, which necessitates running the lamps only in the vertical position. Supports, or rather guides, are fixed to the top of the bulb through which the filaments pass, and these to a certain extent overcome both these troubles.

Compared with carbon filaments the osmium, like all other metallic filaments, are of very low resistance. The specific resistance at the working temperature is approximately 0·000473 ohms per $m/m^2 \times 1\,m/m$, the corresponding figure for carbon filaments being about 0·02 (see p. 110). This has prevented the osmium lamp being perfected for either high voltage or low candle-power. Lamps were made for 110 volts, but the highest voltage lamp commercially introduced was 75 volts, and these were of 32 candle-power. In order to make this lamp, four horseshoe filaments were mounted in series in the bulb, the brittleness of the osmium wire when cold and its softness when hot preventing it from being wound into other shapes which would admit of a greater length of wire in a single filament. The distribution of light with this disposition of the filaments is naturally very good; the horizontal distribution curve is practically a true circle; a vertical

distribution curve for a three-filament lamp is shown in Fig. 66.

The lamps are run at a consumption of 1·6—1·7 watts per candle-power, and maintain their candle-power and efficiency well throughout a long life of about 2,000 hours. The candle-power rises slightly at first, then falls to about its original value and remains practically constant throughout

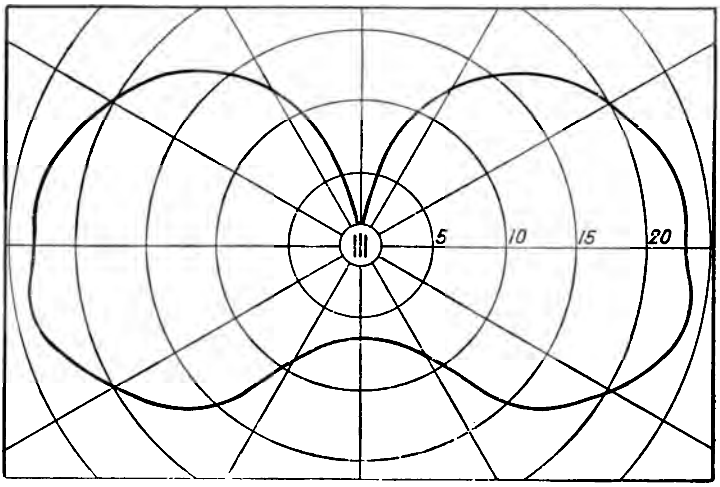


FIG. 66.—Vertical distribution curve. Three-filament osmium lamp.

the remainder of the life, and the average watts per candle throughout the life may be taken as 1·7. The bulbs rarely blacken, and thus one of the chief causes of the deterioration of the carbon-filament lamp is absent.

The resistance of the filament increases with increase of temperature, and thus the current does not rise so rapidly with rise of voltage as it does with carbon filaments. In consequence the candle-power is less affected by voltage

variations than is the case with carbon-filament lamps. Curves showing these variations are given in Fig. 67. The

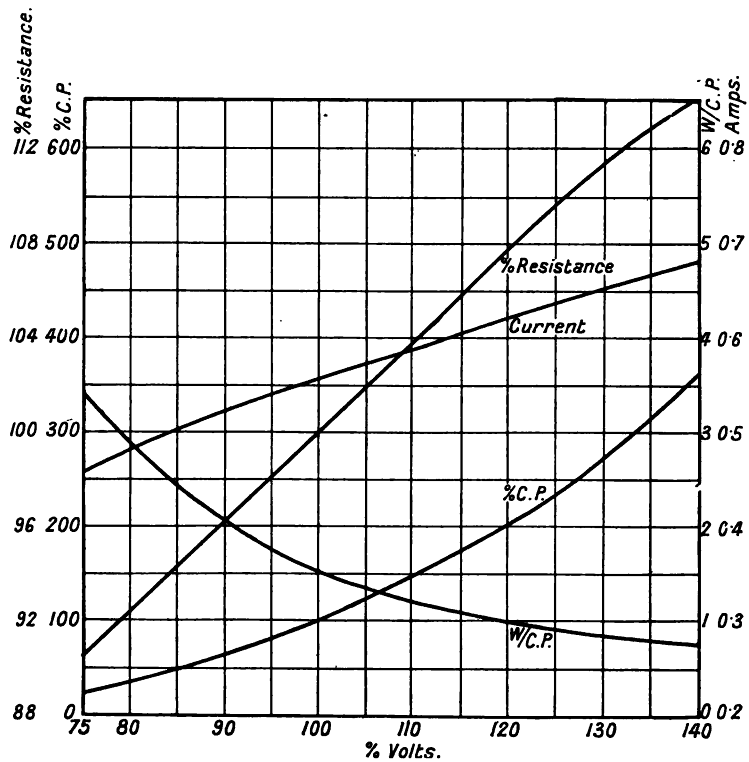


FIG. 67.—Characteristic curves for osmium lamps.

intrinsic brightness at the working temperature is approximately 1·11 candles per square millimetre.

The osmium lamp has been described on account of its interesting position as the first of the new metallic filament lamps. Otherwise the description might have been omitted as the lamp must be regarded at present as

already obsolete, having given place to the tungsten lamp, the filament of which is similar in character to the osmium filament, but in many respects superior.

The Tantalum Lamp.

The earliest patents in relation to the tantalum lamp were taken out by Messrs. Siemens and Halske in 1901 and 1902, but the lamp was not introduced commercially until 1905. During 1906 and 1907 the lamp has steadily grown in popularity, and the number now in use is very large. The tantalum lamp can certainly claim to be the first metallic filament lamp which proved to the full its suitability for commercial use, and however it may be affected by the development of its formidable rival the tungsten lamp, it will continue to be remembered as the first lamp to afford solid ground for the hope of a marked advance in electric incandescent lighting.

Manufacture.—The filament of the tantalum lamp is made from pure drawn tantalum wire, and one of the chief difficulties in its manufacture is the preparation of the pure tantalum in a form suitable for drawing. Tantalum metal is obtained in a powdery form by reducing potassium-tantalo-fluoride: the powder is then fused electrically in vacuo, the process serving not only to produce the metal in a coherent form but also to drive off the occluded gases. The fused ingot is drawn into wire, the precise method by which this is done not being published, but the process must be one of considerable difficulty in view of the extreme hardness of the metal which is, however, ductile and the tantalum wires are quite flexible. The metal oxidises readily, and when heated burns away completely to oxide; the filament

must therefore be mounted in an exhausted bulb, and the difficulty of disposing of the necessary length in the bulb has been overcome in an ingenious manner (rendered possible by the flexibility of the wire) by winding it on a frame as shown in Fig. 68. In this figure, for the sake of greater clearness, only the front half of the frame and filament is shown. This frame is mounted in a bulb in the usual manner. The other details of the lamp call for no special mention. Probably apart from the difficulty in making the original tantalum wire, the lamp is one of the easiest of the metallic-filament lamps to manufacture, which leads to the hope that it may be greatly reduced in price when competition renders this necessary.

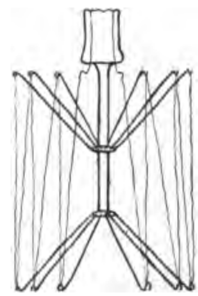


FIG. 68. — Method of suspending tantalum filament.

Performance.—The low specific resistance of the filament has rendered the manufacture of high voltage lamps impossible so far. The specific resistance at the working temperature is approximately 0·00037 ohm per $m/m^2 \times 1$ m/m. In addition to this disadvantage, tantalum lamps possess the drawback that they are unsuitable for use on alternating-current circuits. The reason for this has never been fully explained: it is obvious that there can be no electrolytic action in a filament of pure metal, so that the explanation which will serve to explain the shorter life of Nernst lamps on alternating current will not help in this case. It seems as if the defect is due to mechanical deterioration of the filament caused possibly by rapidly alternating expansion and contraction, or by actual mechanical vibration. Some interesting micro-photographs of tantalum filaments

which have been running a considerable time have been published by various experimenters.[1] These show that the filaments run on alternating circuits appear to break up into a number of very short lengths, the flat ends of which are joined together, but the various lengths are not coaxial, two

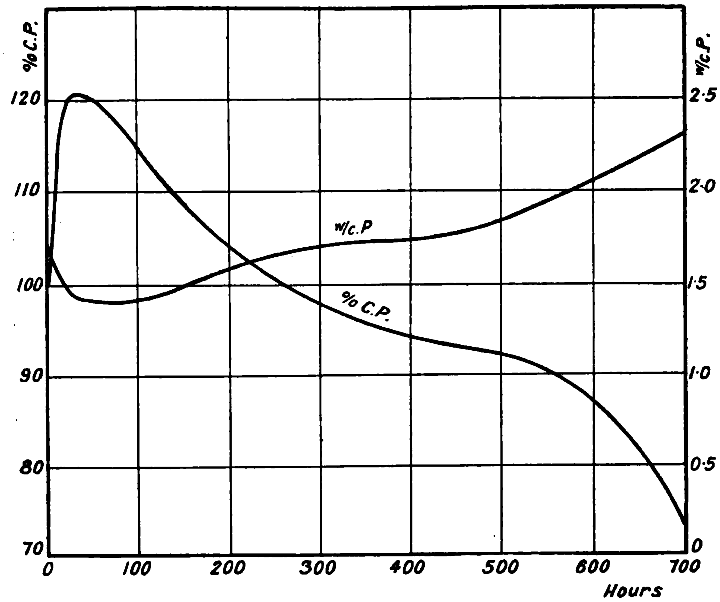


FIG. 69.—Life test curves. 110-volt 25 candle-power, direct-current tantalum lamps.

pieces often being only in contact at their edges, and frequently meeting at an angle. There appears to be some relation between the length of these segments and the

[1] See *The Journal of the Institution of Electrical Engineers*, Vol. XXXVIII., p. 260. *Electrical Engineering*, Vol. I., pp. 108 and 109. *The Electrical World*, Vol. LI., p. 1374.

frequency of the alternating current, but the whole subject is still somewhat obscure and in need of further investigation. It is stated, however, that this difficulty has now been overcome, though at present data are wanting to confirm this claim. The alternating lamps now on the

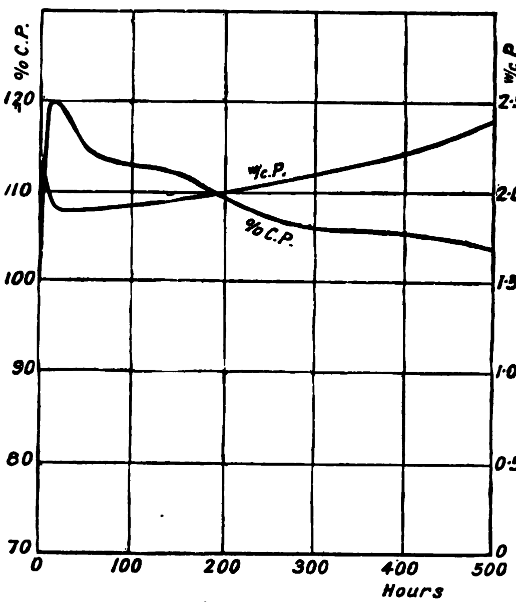


FIG. 70.—Life test curves. 100-volt 17 candle-power alternating-current tantalum lamps.

market give less satisfactory results than the direct-current, although they are run at a lower consumption in watts per candle. The lamps are worked normally at a consumption of 1·6 to 1·7 watts per candle and retain their candle-power and efficiency fairly well throughout a life averaging about 700 hours. There appears in some cases,

but not in all, to be a large initial rise in candle-power and a subsequent fairly rapid fall. The life curves hitherto published vary very greatly[1]: this is doubtless due to want

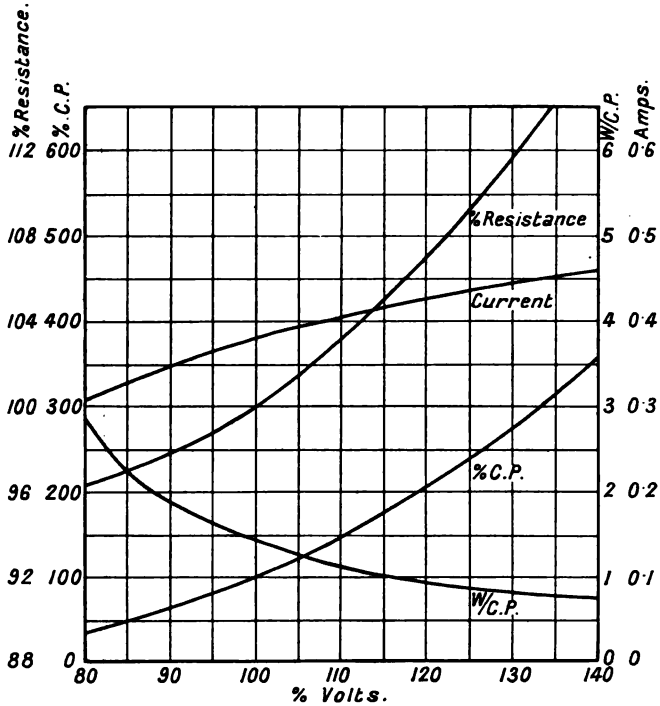


FIG. 71.—Characteristic curves for tantalum lamps.

of uniformity in manufacture, which is only to be expected in the early years of production. In Fig. 69 is given a curve showing the result of a life test on direct-current tantalum

[1] See for example *The Electrician*, Vol. LV., p. 385, June 23, 1905. Tests by Dr. Bell and Prof. Puffer. Also same volume, p. 941, Sept. 29, 1905, tests by Prof. Ambler. And *Electrical Engineering*, Vol. I., p. 107, January 17, 1907, tests by Dr. Sharp.

lamps, and in Fig. 70 a corresponding test on alternating lamps. From these curves the life for the direct-current lamps comes out at 650 hours (life till 20 per cent. fall) at 1·7 watts per candle, and for the alternating-current lamps at 500 hours (life till failure) at 2·1 watts per candle.

The lamps are subject to blackening of the bulb in the same way as carbon-filament lamps, but the blackening is more or less confined to the zone of the globe surrounding the filament, the remainder remaining very clear. This is doubtless due to the proximity of the filament to the glass, and it is probable that other metallic filament lamps would show the same defect if mounted in the bulb in a similar manner.

The resistance of the tantalum filament rises with increase of temperature, and the characteristic curves (see Fig. 71) are very similar to those for the osmium lamp. The rise in candle-power with increase in voltage is naturally much less marked than with carbon filaments.

The distribution of light in the horizontal plane, as would be expected from the way in which the filament is fixed, is remarkably uniform, the horizontal distribution curve being therefore a circle. The vertical distribution curve for a tantalum lamp with half-frosted bulb is given in Fig. 72.

Some tests published by Dr. Sharp[1] in 1906 show that the value of the mean spherical reduction factor for tantalum lamps is very variable: in 10 lamps tested the

[1] *The Electrician*, Vol. LVII., p. 492, July 13, 1906. The results of some similar but less comprehensive tests confirming Dr. Sharp's conclusions were given by Mr. McKinney in a discussion at the Institution of Electrical Engineers. See *The Journal*, Vol. XXXVIII., p. 246, January 17, 1907.

value varied from a minimum of 0·688 to a maximum of 0·764, the mean value being 0·726. This is also to be expected, as the distribution must depend largely on the precise angles made by the several short lengths of the filament with the vertical; for example, the supporting wires may be so arranged that all the filament lengths lie on the surface of a cylinder, or on the surface of a cone

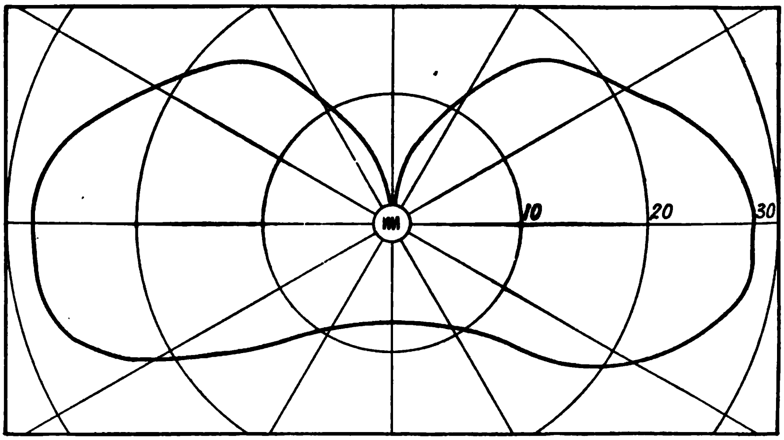


FIG. 72.—Vertical distribution curve. Tantalum lamp, half-frosted bulb.

having a more or less acute angle. It cannot be expected that lamps will be produced with absolute uniformity in this respect. The makers now generally frost the bottom part of the bulb to improve the downward distribution. Another point brought out by Dr. Sharp in the paper just mentioned is that the spherical reduction factor increases as the lamp ages. This is due to alteration in the filament itself, to alteration in the shape of the surface on which the filament lengths lie, and to the blackening of the

vertical sides of the bulb. The latter is probably the chief cause, since it must bring about a much greater diminution in the mean horizontal candle-power of the lamp than in the candle-power in other directions. The mean spherical reduction factor for the ten lamps already quoted was found by Dr. Sharp to have risen after use to 0·897. The phenomenon is one of considerable importance in view of the fact that life test results are generally obtained on the basis, at best, of mean horizontal candle-power. Such a method of testing, since it assumes constancy of the spherical reduction factor is shown by the above results to be particularly unfair to tantalum lamps, which will be credited with less candle-power when old than they are actually giving. This serves to emphasise again the importance of all tests which profess to be scientific, being based on actual measurements of mean spherical candle-power. In addition the rating of tantalum lamps by mean horizontal candle-power is less satisfactory than the same practice with carbon lamps, for whereas the spherical reduction factor for different carbon lamps of the same type may be assumed the same, this cannot be done in the case of tantalum lamps.

The intrinsic brightness of the filament of the tantalum lamp is approximately 1·38 candles per square millimetre.

The Tungsten Lamp.

The earliest patents relating to the production of filaments of tungsten appeared in 1904. The most important are those taken out by Just and Hanaman, Kuzel, and Welsbach. In 1905 and 1906 many other patentees covered processes for manufacturing these filaments, but it must be remembered that by this time the possibilities of the

metallic-filament lamp were becoming well recognised, and many who patented methods and processes probably did so only in the hope that their ideas might some day prove fruitful. The credit for the development of a commercial lamp rests with the inventors already named, and lamps are now manufactured by all three of the processes which they devised. It is too early to say which of these is likely to survive; possibly some modification combining the advantages of all will prove ultimately the most efficient and reliable manufacturing process.

The tungsten lamp appears to have a brilliant future before it. Whilst in its present form it lacks some of the advantages of the tantalum lamp, the fact that the consumption of power per candle is only about half that with tantalum will cover a great many defects. Unless a new metal filament is brought forward with an efficiency markedly superior, it is difficult to see what competitor now in the field can stand long against the tungsten filament.

Manufacture.—The three patented methods of producing tungsten filaments are as follows:—

(1) *Just and Hanaman's Process.*[1]—The basis of this method is the preparation of a carbon filament in the usual way, covering this with a deposit of tungsten by "flashing" in an atmosphere of some volatile tungsten compound (*e.g.*, tungsten chloride), and finally removing the carbon by incandescing in an atmosphere of water-vapour and hydrogen, at the same time sintering the resulting tungsten filament. It is necessary, in order to produce fine tungsten filaments in this way, to start with a carbon filament of

[1] English Patents, 23,899, 1904; 11,949, 1905; 20,175, 1905; 20,175a, 1905; 3,225, 1906.

very small diameter. An improvement in this direction is probably effected by the method (also described in the patent) of incorporating some of the tungsten in the original carbon filament before carbonisation by adding tungsten to the mixture from which the thread is squirted. The chief difficulty in this process, however, appears to be the thorough removal of the carbon. Carbon left in the finished filament is fatal to the good performance of the lamp. Mr. Swinburne has referred to the method of sweating out the carbon as heroic; it is an act of heroism which factory girls can be trained to perform at piece-work prices, but it is still a difficult process from the point of view of obtaining uniform results with certainty. The process naturally results in the production of a tubular filament, an advantage from the point of view of the manufacture of high resistance filaments suitable for low candle-powers and high voltages.

(2) *Kuzel's Process.*[1]—The difficulty of having to remove carbon is overcome by squirting the filament direct from finely divided tungsten without the use of any organic binding agent. Very finely divided tungsten is needed for this purpose, and this is obtained by burning an arc between electrodes of tungsten under water. This results in a pseudo-solution of the tungsten, which passes into the water in a very finely divided condition, forming what is known as a "gel." This emulsion or solution of colloidal tungsten may be evaporated down to partial dryness, and a fine thread of tungsten then squirted from it. The filaments thus made have to be subjected to the usual incandescing and sintering processes.

[1] English Patents, 28,154, 1904; 15,462, 1905; 5,129, 1906; 7,655, 1906; 8,057, 1906.

(3) *Welsbach's Process.*[1]—The Welsbach process for the production of tungsten filaments is simply a development of the process for making osmium filaments, which has already been described, tungsten being used instead of osmium as the basis of the filament. To maintain the connection between the osmium lamp and the Wolfram (tungsten) lamp, the tungsten lamps made by this method were, and still are, called "Osram" lamps. They have, however, no osmium in the filament.

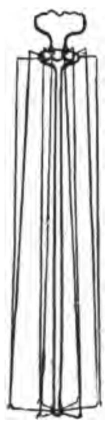


FIG. 73.—Method of supporting tungsten filament.

The only special difficulty in the further manufacture of tungsten lamps after the filament has been produced is presented by the mounts and supports. Two methods of mounting have been used; in the one the filament is pasted on with a paste containing tungsten, in the other it is fused electrically on to the supporting wire. The supports or guides through which the free ends of the filaments pass are made from, or covered with, a highly refractory material, as, but for this precaution, if the incandescent filament touches the support, it will inevitably stick to it. In some of the lamps now made the ends of the filaments, instead of passing through guides, are hooked over wire supports, as shown in Fig. 73; in this way a slight tension can be put on the filament, enabling the lamp to be used in any position. The other details of manufacture do not call for special comment.

[1] English Patents, 18,814, 1905; 19,379, 1905.

Performance.—The tungsten filament is, like the osmium, brittle when cold and soft when hot, but is very considerably superior to the osmium filament in both these respects. The lamps can, however, only be used in a vertical position, unless the filaments are mounted as described above.

The specific resistance of the tungsten filament at the working temperature is approximately 0·000282 ohms per

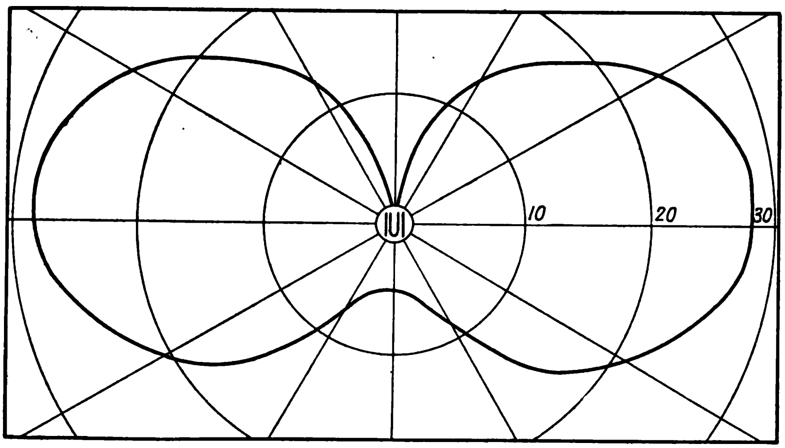


FIG. 74.—Vertical distribution curve. Four-filament Osram lamp.

$m/m^2 \times 1\ m/m$. In common, therefore, with other metallic filament lamps, the tungsten lamp is difficult to make for high voltages and low candle-powers. Lamps are, however, now made in the higher candle-powers (45—100) for 200 volts and in candle-powers from 20 to 100 for low-voltage circuits. The high-voltage lamps have 6 filaments and the low-voltage lamps 4; the horizontal distribution, with a number of horseshoe filaments, is naturally practically

uniform. A curve, showing the vertical distribution for a 110-volt 32 candle-power lamp, is given in Fig. 74.

The power consumption is normally about 1·2—1·4 watts per candle. Both candle-power and efficiency are remarkably well maintained during life. The curve in Fig. 75 gives the test result on some 100-volt 20 candle-power lamps, from which it will be seen that, even after a life of 1,600 hours, the fall in candle-power was less than 10 per

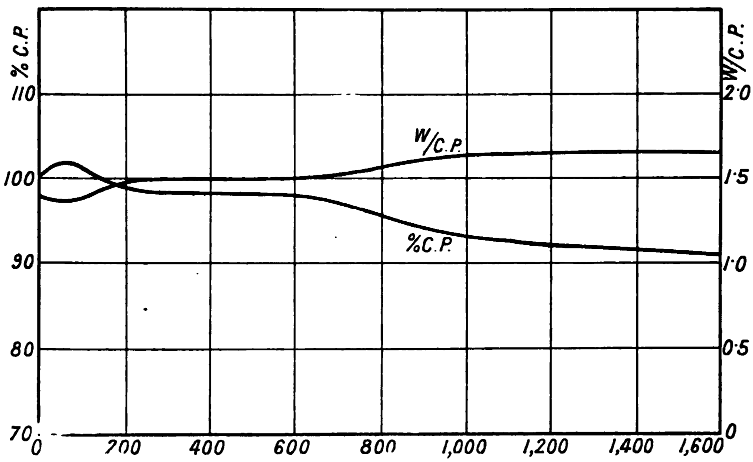


FIG. 75.—Life test curve. 100-volt 20 candle-power Osram lamps.

cent. These particular lamps are somewhat low in efficiency (the consumption starting at 1·4 $w/c.p.$), but equally good results have been obtained with lamps of higher efficiency,[1]

[1] See for example the curves given by Prof. Grau in *The Illuminating Engineer*, Vol. I., p. 186, March, 1908. A number of life test results have been published by Mr. Hirst in a paper on "Recent Progress in Metallic Filament Lamps," read before the Institution of Electrical Engineers since the abeve was written. The results more than confirm the conclusion as to average life and consumption drawn above. See *Electrical Engineering*, Vol. III., p. 805.

and it is to be noted that the lamps tested for Fig. 75 are 20 candle-power. It is too early to say what may be

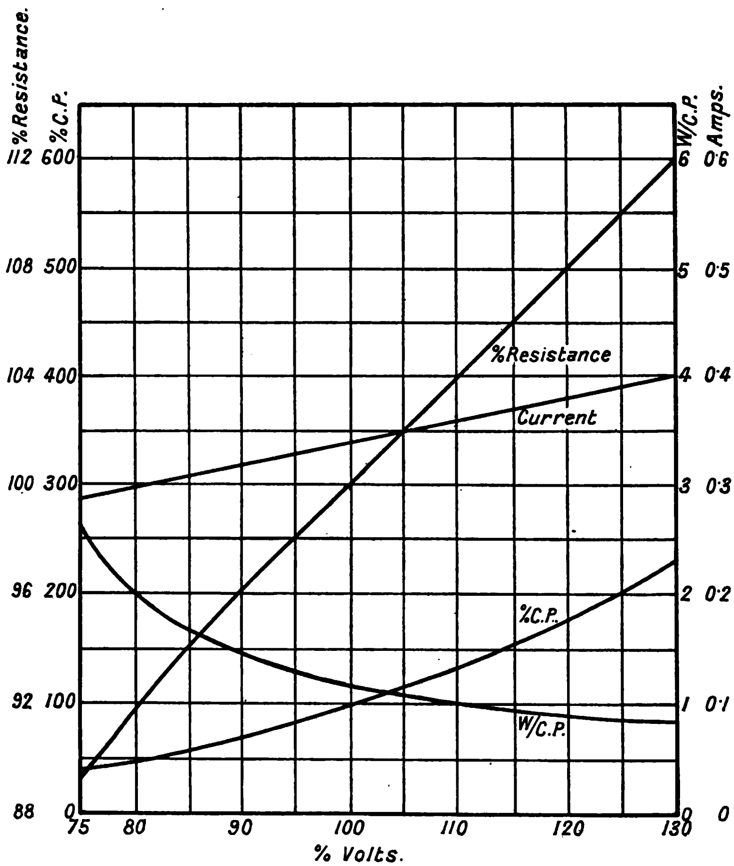


FIG. 76.--Characteristic curves for tungsten lamps.

regarded as the average life for tungsten lamps, but probably 1,500 hours at an average consumption of 1·4 watts per candle during the life is not far from correct.

The lamps do not often blacken, though some show this defect, and generally when it does occur blackening takes place both rapidly and to a marked degree. The defect

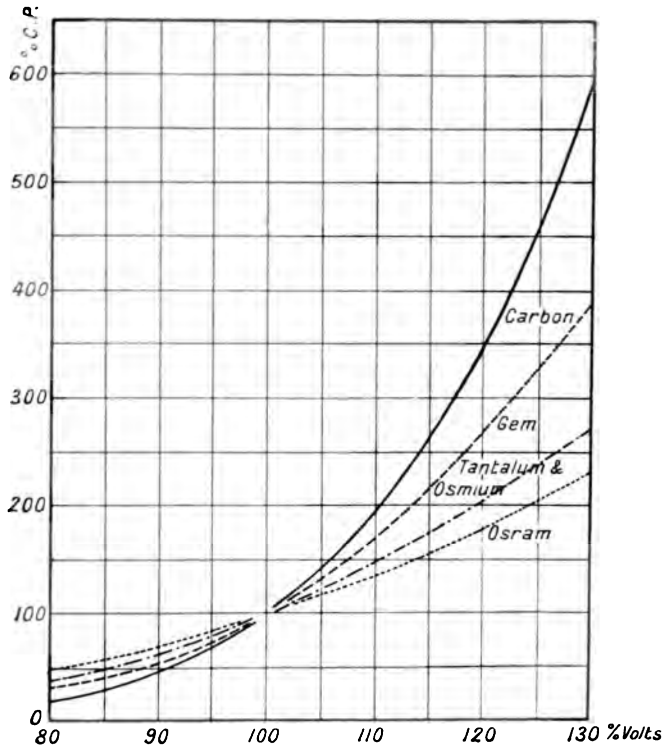


FIG. 77.—Variation of candle-power with voltage: various lamps.

probably lies in faulty manufacture, and is likely to be greatly minimised, if not entirely removed, as more experience is gained.

Curves showing the variation of candle-power, etc., with variation of voltage, are given in Fig. 76, and have the

usual characteristics of these curves for metallic-filament lamps. The intrinsic brilliancy of the filament at working temperature is 2·18 candles per square m/m.

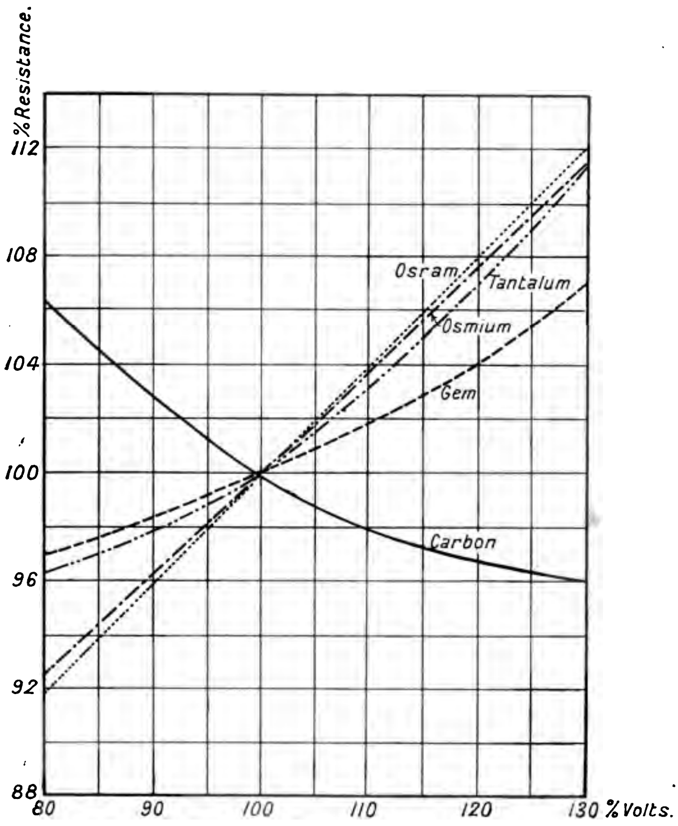


FIG. 78.—Variation of resistance with voltage: various lamps.

CONCLUSION.

Individual curves have already been given showing the characteristics of the various filaments used in incandescent

lamps. For convenience of comparison the curves for percentage variation of candle-power are replotted together in Fig. 77, and the curves for percentage variation of resistance are replotted in Fig. 78. The essential difference between the carbon filament and metallic filaments is clearly brought out by these curves, and the intermediate position occupied by the metallised carbon filament is well seen. The curves shown were all obtained by the writer; a number of similar curves have been published,[1] which agree in general characteristics with those given here. As has already been pointed out, curves of this type must only be taken as typical, as there are always small differences between individual filaments. One consequence of the positive temperature coefficient of the metallic filament is that there is always an overrush of current when the lamp is switched on. Mr. Morris,[2] who has studied this with the oscillograph, found the following ratios of starting and final current:—

TABLE XVII.

Lamp.	Ratio of Starting Current to Final Current.	
	Calculated from Resistance Curves.	Observed with Oscillograph.
Carbon filament . .	—	0·569 : 1
Tantalum . . .	5·73 : 1	4·74 : 1
Tungsten . . .	12·43 : 1	7·33 : 1

This peculiarity may possibly give rise to trouble in

[1] See for example a paper by Messrs. Morris, Stroude and Ellis, *The Electrician*, Vol. LIX., p. 584.

[2] *The Electrician, loc. cit.* See also *Journal I. E. E.*, Vol. XXXVIII., p. 253.

switching on large clusters of metallic-filament lamps, but as the high current lasts only about $\frac{1}{1000}$th of a second, the difficulty is hardly likely to be serious.

It is convenient to calculate here the cost of lighting with the two commercial types of metallic-filament lamp now on the market. For this purpose, the life of the tantalum lamp has been taken as 700 hours at 1·7 watts per candle for direct-current, and 500 hours at 2·1 watts per candle for alternating-current, and the life of the tungsten lamp as 1,500 hours at 1·3 watts per candle, direct or alternating-current. As the figure of 1,500 hours may be possibly regarded as too great, the costs have also been worked out on the assumption that the life is only 1,000 hours. The costs of the lamps have been taken as 2*s*. 3*d*. for the tantalum, and 4*s*. for the tungsten lamps.

TABLE XVIII.

TOTAL COST OF LIGHTING PER 1,000 CANDLE-HOURS. METALLIC-FILAMENT LAMPS.

Cost per B.O.T. Unit.	1*d*.	2*d*.	3*d*.	4*d*.	5*d*.	6*d*.	7*d*.	8*d*.
Tantalum, direct-current	3·2	4·9	6·6	8·3	10·0	11·7	13·4	15·1
Tantalum, alternating current . . .	4·3	6·4	8·5	10·6	12·7	14·8	16·9	19·0
Tungsten, 1,500 hours .	2·4	3·7	5·0	6·3	7·6	8·9	10·2	11·5
Tungsten, 1,000 hours .	2·9	4·2	5·5	6·8	8·1	9·4	10·7	12·0

A matter of considerable interest in connection with metallic-filament lamps is the question of series running. As these lamps, in small units, can only be obtained for low voltages, the necessity has arisen, where the supply is at

high voltage, for running two or more lamps in series. Even now that the tungsten lamp is becoming available for the higher voltage this necessity still exists to a certain extent, as these higher voltage lamps are of fairly high candle-power. It was at first feared that series running would give rise to great difficulties, but these fears have hardly been justified by actual experience. It is true that to obtain satisfactory results it is necessary that the two lamps used in series should be properly paired so that both take the same current, as otherwise one lamp will be overrun with a detrimental effect on its life. But, fortunately, this fact has been very fully recognised by the manufacturers, who have, especially in the case of the tungsten lamps, taken elaborate precautions in the grading of the lamps to enable them to be sold accurately paired. There is consequently now no difficulty in installing properly paired lamps at the start, or in replacing one which fails by another which will pair properly with the survivor. Where supply is on the alternating-current system series running may be dispensed with, the voltage being transformed down instead; this is a very considerable advantage, as it enables much lower voltages than usual to be employed (25—50 volts), and consequently makes possible the use of still smaller light units.

The metallic-filament lamp is beyond question destined to have a very great effect on the electric lighting industry, both on the commercial and the technical side. It is not possible to discuss this question fully here, but some of the more important aspects will be considered in the last chapter.

CHAPTER VIII

THE ELECTRIC ARC

If two pieces of carbon, connected to terminals between which a potential difference of about 50 volts is maintained, are brought into contact and then drawn a short distance apart, an arc is formed in the following manner:—At the moment of contact a current flows around the circuit; on separating the two carbons a spark occurs, and some of the carbon is volatilised, forming a conducting vapour bridge between the carbons, across which the current continues to flow from one carbon to the other. This vapour bridge or flame is the arc proper; when moderately pure carbons are used the arc is violet in colour and gives but very little light. The tips of the two carbons, however, become heated white hot over a small part of their area and form intensely powerful sources of light. The vapour bridge itself can also be made a source of light by introducing certain substances into the carbons which are volatilised into the arc and convert it into a luminous flame. In the ordinary open and enclosed types of arc lamps the intensely heated carbon tips form the light-giving source; in the flame arc lamp the light is derived partly from the carbon tips, but chiefly from the luminous flame.

The discovery of the arc is generally attributed to Sir Humphry Davy in the year 1801. Mrs. Ayrton has shown, however, that the particular experiment cited is an

experiment with a spark between charcoal points rather than with an arc, and that it is probable that no clear distinction between the spark and the arc was recognised at first. The actual first recognition of the arc as a distinct phenomenon must therefore remain obscure; the first unmistakable description of the true "arch" of flame which gave the arc its name is due to Davy in 1812.

Since the true recognition of the arc, and its use as a source of light, the phenomena which occur have formed the subject of continuous research. In the present chapter an attempt will be made to summarise the more important results, particularly those having a direct bearing on the use of the arc as an illuminant. It is impossible, in the necessary limits, to deal with the subject fully; it is, moreover, unnecessary, since the ground is already covered by Mrs. Ayrton's book on "The Electric Arc."[1] In this book Mrs. Ayrton discusses the results of all the more important researches on the arc in addition to her own work. It is impossible to write on the general theory of the arc without realising at every step one's indebtedness to Mrs. Ayrton; throughout this chapter, therefore, references generally will not be given to Mrs. Ayrton's book, but the reader who wishes to obtain a fuller insight into any of the questions discussed is referred thereto at the outset. My thanks are also due to Mrs. Ayrton for permission to reproduce a number of the curves given in her book.

The Appearance of the Arc.—The appearance of the arc can be seen fairly well after a little practice by observing it through coloured glass, but the only really satisfactory method is to obtain an enlarged image on a screen by

[1] Published by *The Electrician* Printing and Publishing Co., London.

means of a lens. In Fig. 79 is shown a drawing of a direct-current arc burning between an 18 m/m cored positive and a 12 m/m solid negative carbon. The arc length is 2 m/m, the current 10 amperes, and the potential difference between the carbons 40 volts. It will be seen that the positive carbon burns to a blunt point. The end of this point is not, however, flat, but is hollowed out to form a small "crater." This crater is somewhat larger in diameter than the core of the carbon, and practically the whole of its surface is at an intense white heat. The whole of the conical point of the carbon is at a high temperature, which falls away gradually from a white heat at the tip to cold farther up the carbon. At a short distance from the tip is a mantle or fringe from which the point appears to start; this fringe is formed from the outer surface of the carbon and its edge is irregular and generally formed of small globules of molten impurities. A white overlapping mantle of substances volatilised from the core (and the carbons) also forms to a greater or lesser extent. The end of the negative carbon also burns to a point which is much sharper than is the case with the positive carbon. There is no crater on the end of the negative carbon (unless, which is unusual, a cored negative carbon is used), but the actual tip on which the arc appears to rest is at an intense white heat, and the

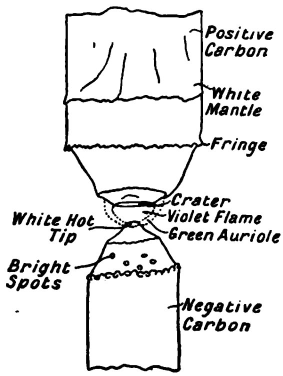


FIG. 79. — Direct-current open arc between 18 m/m cored and 12 m/m solid carbons.

temperature decreases away from this point in the same way as on the positive carbon. A number of bright spots develop on the point of the negative carbon, and a fringe similar to that which forms on the positive is also present. Between the two carbons is a violet flame surrounded by a dark space, and then an outer green auriole. At its points of contact with the two carbons the arc is practically colourless.

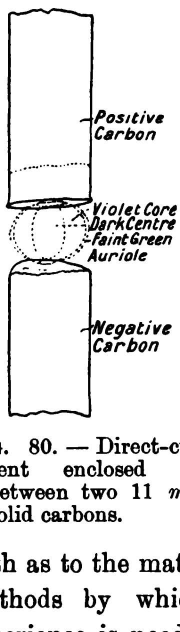


FIG. 80. — Direct-current enclosed arc between two 11 m/m solid carbons.

The precise shapes assumed by the two carbons as they burn depend on the conditions under which the arc is burning and the quality of the carbons. Mrs. Ayrton has pointed out that, using carbons of given size and quality, it is possible to tell from the shapes of the points precisely the conditions under which they have been burnt. It is equally true that burning always under the same conditions it is possible to learn from these shapes a great deal about the quality of the carbons, both as to the materials used in their manufacture and the methods by which they have been made. Naturally experience is needed in both cases to form a judgment of any value.

In Fig. 80 is shown the appearance of an enclosed arc, that is, an arc burning between carbons enclosed in a nearly air-tight globe. The carbons are both 11 m/m diameter and both solid, the current 5 amperes, and the potential difference between the carbons 85 volts. The

ends of both carbons are nearly flat, but the end of the positive carbon is found on examination to be covered with a number of very small craters, and is generally also slightly larger in diameter than the original carbon. If the arc is watched whilst it burns, it will be seen to wander incessantly from one part of the carbon to another, burning for a short time in each position; this accounts for the pitting of the carbon and for the fact that it burns with a flat end. The absence of any pointing of the carbons with the enclosed arc shows that this is simply due to the burning away of the carbons where the air obtains access to their hot surfaces. The enclosed arc itself is much longer than the open arc (8 m/m in the case illustrated), to which in general appearance it is similar.

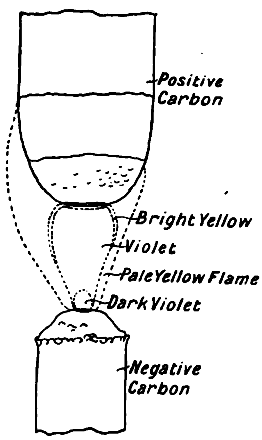


FIG. 81. — Direct - current flame arc between 18 m/m flame-cored and 12 m/m ordinary-cored carbons.

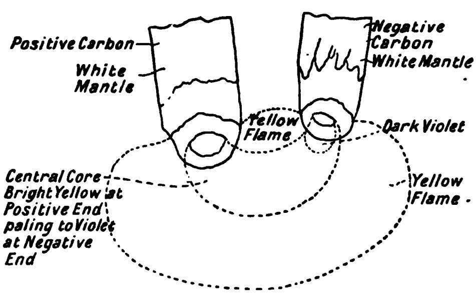


FIG. 82.—Direct-current flame arc between 8 m/m flame-cored and 7 m/m ordinary-cored inclined carbons.

In Fig. 81 is a drawing of a flame arc burning between an 18 m/m flame-cored positive and a 12 m/m ordinary-cored negative

carbon arranged vertically as in an ordinary open arc. This is not a very usual arrangement for flame carbons, but is interesting as being more comparable with an ordinary open type arc. The large luminous flame is the chief point to be noticed. In Fig. 82 is a drawing of a flame arc burning between an 8 *m/m* flame-cored positive and a 7 *m/m* ordinary-cored negative carbon arranged in the manner most commonly employed for flame lamps. As can be seen from the figure, the carbons are arranged in the lamp so that they are inclined to one another at an angle of about 30°. The arc burns across from the tip of one carbon to the tip of the other, and consists of a long, luminous flame: both carbons being cored there is a marked crater on both positive and negative. The arc is constrained to keep at the ends of the carbons by deflecting it by means of a magnetic field.

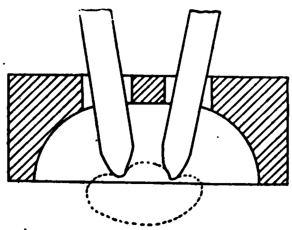


FIG. 83. — Arrangement of carbons and economiser in flame arc lamps.

A little way above the arc is a reflecting cup-shaped cover of fireclay or metal (see Fig. 83); this serves a double purpose; in the first place it acts as a reflector, throwing downwards the light which would be otherwise lost in the upper part of the lamp. Secondly, it causes the carbons to burn in an atmosphere of spent gases comparatively free from oxygen, and thus considerably lowers the rate at which they burn away: on account of this property it is known as an economiser.

The characteristic shapes of the carbons are not attained until after the arc has been burning for some time under

the correct conditions; the time varies greatly, being longest when the current is small compared with the diameter of the carbons; under extreme conditions an hour or more may have to elapse. Until the carbons have assumed their proper shapes the relation between P.D. and current does not assume its final steady value. For this reason lamps will not burn at their best when first switched on with new carbons, and in order to reduce as much as possible the time before which steady results are obtained, the carbons should be pointed by the manufacturer to a shape resembling as closely as possible that which they will ultimately assume. In practice, a fairly blunt conical point is put on by all manufacturers for open type carbons, and the ends of enclosed carbons are left flat, as naturally all the possible conditions of burning cannot be provided for, but carbons for special work such as searchlight and cinematograph carbons are generally given points exactly the same shape as they attain by burning.

The Length of the Arc.—The length of the arc is defined as the distance between the plane of the mouth of the crater and the tip of the negative carbon. It is possible, therefore, to have an arc of negative length; this is merely a question of definition; the method adopted of measuring from the mouth of the crater has become general on account of its convenience.

When the current is kept constant the P.D. between the carbons increases as the length of the arc is increased. The laws connecting the variation of P.D. with the length of the arc are different according as the carbons used are solid or cored. In Fig. 84 are shown P.D. and length of arc curves for a 10-ampere arc with both carbons solid, and

positive cored and negative solid. With both carbons solid this curve is a straight line, and if a number of these curves be drawn for different currents it is found that they all meet in a point to the left of the axis of P.D., *i.e.*, a point corresponding to a negative length of arc. In Fig. 85

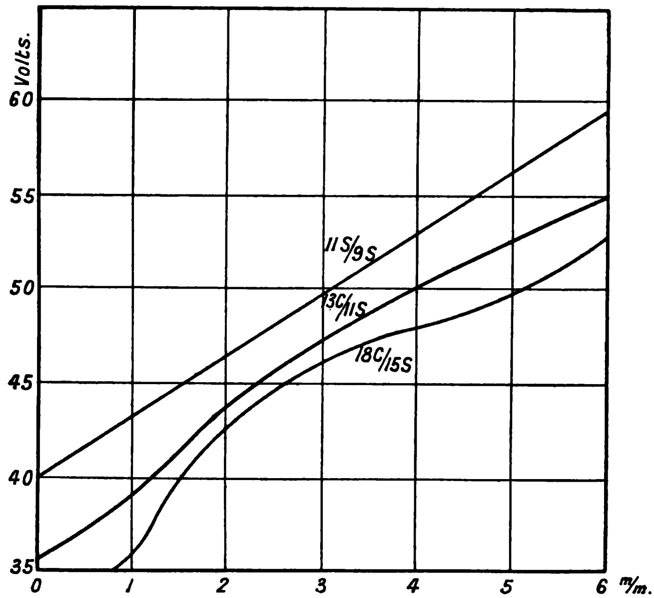


FIG. 84.—P.D.-length of arc curves. Direct-current 10-ampere open arcs. (From "The Electric Arc." Mrs. Ayrton.)

are shown the curves connecting P.D. and length of arc with different currents for arcs burning between an 18 *m/m* cored positive and a 15 *m/m* solid negative carbon, the usual condition in practice. These curves do not meet at a definite point, but for a length of arc of 2 *m/m* the P.D. is approximately independent of the current. For shorter

lengths than this the higher the current the higher the P.D.; for longer lengths this relation is reversed. The curves connecting P.D. and length of arc for two cored carbons are similar to those in Fig. 85, but the point of intersection is much more definite.

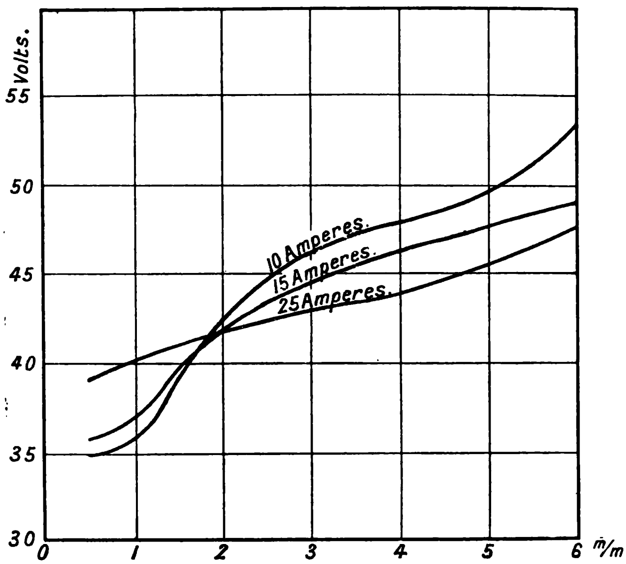


FIG. 85.—P.D.-length of arc curves. Direct-current open arc. Carbons: 18 m/m cored/15 m/m solid.
(From "The Electric Arc." Mrs. Ayrton.)

The length of arc corresponding to a given current and P.D. is longest when both carbons are cored and shortest when both carbons are solid. Coring the negative carbon has, however, less influence on the length of the arc than coring the positive carbon. The composition, and to a certain extent the diameter of the core, have great influence

on the length of the arc. The material used for coring ordinary carbons is very finely ground carbon, of approximately the same composition as the carbon rod itself, mixed to a paste with a solution of potassium silicate. The composition and the percentage of the silicate used influence considerably the length of the arc. The fact that the introduction of the flame-producing material into the core of the positive carbon increases the length of a 10-ampere 40-volt arc from 2 to about 14 millimetres need only be mentioned to show the effect which can be produced by altering the composition of the core.

Size of the Crater.—Mrs. Ayrton has shown that the alterations in the laws connecting P.D.-current and length produced by coring the positive carbon can all be traced to the alteration in the crater surface. When a solid positive carbon is used the whole of the crater surface consists of solid (hard) carbon; with a cored positive carbon a variable portion of the crater surface consists of core (soft carbon).[1] When the crater is small its surface consists entirely of core; as it increases in size it consists partly of core and partly of solid carbon, the proportion of solid carbon increasing the larger the crater becomes. Now Mrs. Ayrton has shown that with a cored positive carbon the area of the crater increases with the length of the arc when the current is constant, and increases with the current when

[1] The use of the terms hard and soft carbon is to be deprecated; as used by Mrs. Ayrton they have a perfectly definite significance, but generally they are used most loosely, and one person calls a particular quality of carbon hard which another calls soft. Moreover, faults are attributed to carbons being too soft or too hard which have nothing whatsoever to do with this property.

the length of arc is constant. Hence with constant current we should expect the P.D. for a cored-solid arc to be considerably lower than that for a solid-solid arc when the length is short, because with the short arc the crater in the case of the cored-solid arc will lie wholly on the core. As

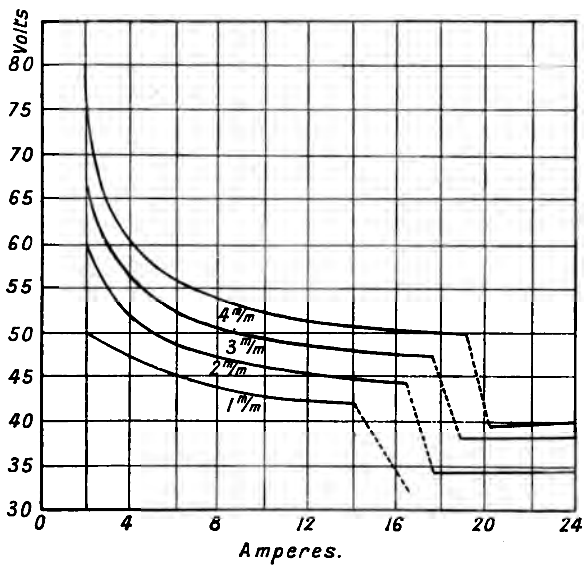


FIG. 86.—P.D.-current curves. Direct-current open arc. Carbons: 11 *m/m* solid/9 *m/m* solid.
(From "The Electric Arc." Mrs. Ayrton.)

the arc length is increased, a point will be reached at which the crater in the case of the cored-solid arc will cover part of the solid carbon, and from this point the P.D. will rise, rapidly at first and then more slowly, becoming more and more nearly equal to that for a solid-solid arc. This is just what is shown by the curves in Fig. 84.

It is equally clear that, provided the diameter of the

crater is greater than that of the core, the larger the core the more the P.D. of the cored-solid arc will be lowered below the corresponding value of the solid-solid arc. This lowering of the P.D. may be traced, as already pointed out, to the presence of potassium silicate in the core, which is volatilised, after decomposition, into the arc, and anything which tends to create a proportionately larger supply of

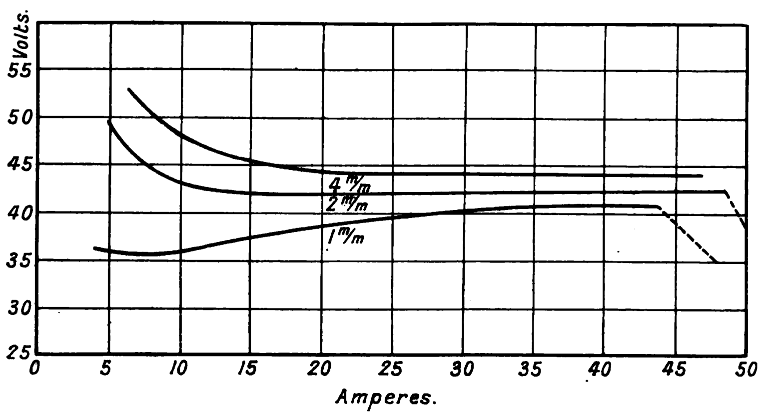


FIG. 87.—P.D.-current curves. Direct-current open arc. Carbons: 18 m/m cored/15 m/m solid.
(From "The Electric Arc." Mrs. Ayrton.)

these vapours in the arc will have the effect of proportionately lowering the P.D.

Potential Difference and Current.—The curves connecting the potential difference and current for constant length of arc have been studied in great detail by Mrs. Ayrton. In Fig. 86 are shown the curves connecting P.D. and current for a solid-solid arc, and in Fig. 87 the corresponding curves for a cored-solid arc. It will be seen that with solid-solid arcs the P.D. falls as the current is increased, at first rapidly

and afterwards more slowly. With cored-solid arcs the P.D. at first falls and afterwards remains practically constant, or even rises. This is a natural consequence of the increase of the area of the crater with increase of current, the fall of P.D. due to the increase of current being balanced, or more than balanced, by the increase of P.D. due to the inclusion of solid carbon in the crater surface. From the fact that the P.D. falls as the current increases (over all ranges of current common in practice, whether the arc is cored-solid or solid-solid), it follows that the arc is an unstable phenomenon. This question has already been discussed fully in connection with the characteristic curves of the Nernst filament (see p. 146), so that it need not be again investigated. It follows, therefore, that an arc cannot be maintained without a resistance in series with it. The arc is, however, not so unstable as the Nernst filament, especially with the currents common in practice and with cored-solid arcs, so that it is not necessary to use a high resistance, or one having the special properties characteristic of the iron wire resistances used in Nernst lamps.

Various attempts have been made to deduce an equation connecting the potential difference, current, and length of arc. The most successful is that of Mrs. Ayrton, who calculated for the curves shown in Fig. 86, the equation

$$V = 38{\cdot}88 + 2{\cdot}074\, l + \frac{11{\cdot}66 + 10{\cdot}54\, l}{A},$$

where V is the P.D. in volts, l the arc length in millimetres, and A the current in amperes. It must be remembered that this equation applies only to the particular carbons (size and quality) used in Mrs. Ayrton's experiments, from

which this set of curves was obtained. It is probable, however, that an equation of the same form, namely,

$$V = a + b\,l + \frac{c + d\,l}{A},$$

will apply to all solid-solid arcs. The equation for cored-solid arcs will necessarily be more complicated. Mr. Duddell[1] has shown that Mrs. Ayrton's equation no longer holds if the arc is longer than the longest with which she worked, the calculated curve departing more and more from the observed curve the greater the length of the arc. Mrs. Ayrton's equation must be taken therefore only as the closest approximation yet obtained; probably terms containing higher powers of l and A exist in the full equation.

Back E.M.F. and Resistance of the Arc.—If the current be constant, Mrs. Ayrton's equation reduces to the form

$$V = m + n\,l$$

where m and n are constants. It is to be noted that the actual values of m and n depend on the value of the current. This equation indicating a constant portion of the P.D. independent of the length of arc, gave rise to the belief in the existence of a back E.M.F. in the arc. In order to discover whether such a back E.M.F. existed or not, and if it existed to determine its value, attempts have been made to measure the *true* resistance of the arc. If we have an arc burning at 10 amperes with a P.D. of 42 volts, then the *apparent* resistance of this arc is $\frac{42}{10} = 4{\cdot}2$ ohms.

[1] "On the Resistance and Electromotive Forces of the Electric Arc." *Transactions Royal Society*, Series A., Vol. CCIII., p. 305, 1904.

Now let the current be increased by a small amount $d\,A$; if the increase in current is so small and is maintained for so short a time that it produces *no* effect on the arc itself, it will be accompanied by a rise in potential difference $d\,V$, such that

$$d\,V = r\,d\,A$$

where r is the *true* resistance of the arc. In order, therefore, to determine r we must find the value of $\frac{d\,V}{d\,A}$ for a small and rapid rise (or fall) in current. The method adopted to carry this out in practice is to superimpose on a direct-current arc a small rapidly alternating current, and to measure the values of the alternating P.D. and current. In the earlier experiments it was not realised sufficiently that the arc is affected by all but extremely rapid fluctuations, and the results obtained are vitiated in consequence. In 1904 Mr. W. Duddell communicated the results of an elaborate research on this point to the Royal Society.[1] Mr. Duddell showed that the R.M.S. value of the alternating P.D., divided by the R.M.S. value of the alternating-current, gave the true resistance of the arc, provided that the power factor of the arc under the testing conditions was unity and remained unity over a considerable range of frequencies. By using frequencies up to 120,000 cycles he was able to satisfy these conditions, with the result that he found for a 3 *m/m* 10-ampere arc between 11 *m/m* solid carbons a resistance of 3·81 ohms and a back E.M.F. of 12 volts; and for a 3 *m/m* 10-ampere arc between 11 *m/m* cored carbons a resistance of 2·54 ohms and a back E.M.F. of 16·9 volts.

[1] *Loc. cit.*

From further experiments Mr. Duddell deduced the conclusion that the back E.M.F. consists of two parts, a back E.M.F. of about 17 volts opposing the current at the positive carbon, and a forward E.M.F. of about 6 volts assisting the current at the negative carbon. The resistance appears also to be divisible into three parts, a resistance of about 1·6 ohms at the positive carbon, a resistance of about 1·2 ohms at the negative carbon, and a resistance in the arc of about 0·4 ohm per millimetre length.

Mrs. Ayrton, in the last chapter of her book, which is worthy of very careful attention from those who are interested in the mechanism of the arc, discusses fully the experiments on measuring the *true* resistance of the arc made up to that time (which do not include those in Mr. Duddell's paper). She points out that the arc itself must be composed of three distinct parts, a film of true carbon vapour resting on the surface of the crater, a carbon mist forming the body of the arc, and a flame enclosing this mist as an envelope where the carbon particles come into contact with and burn with the surrounding air. Of these three distinct parts the flame has a very high specific resistance, the carbon vapour a lower, but still high, specific resistance, and the carbon mist a comparatively low specific resistance. By tracing the alterations in the areas and lengths of these various parts under different conditions, Mrs. Ayrton shows that the laws connecting the different variables (P.D., current, etc.) can be deduced without any necessity for assuming the existence of a back E.M.F. The final paragraph may be quoted in full.

"Thus all the principal phenomena of the arc, with

cored and with solid carbons alike, can, with one exception, to be presently alluded to, be explained as natural results of the variations in the specific resistances of the material in the gap that *must* exist, together with the observed variations in its cross-sections. It is quite probable, therefore, that there is neither a large back E.M.F. in the arc nor a 'negative resistance,'[1] but that its resistance follows the ordinary ohmic laws, obscured only by the varying resistivities of its different parts consequent on their varying temperatures and on the resultant differences in their physical conditions. There is only one phenomenon that these variations do not explain, viz., the fall of potential between the arc and the *negative* carbon, which has been shown to vary between about 8·3 and 11 volts, with currents over 4 amperes. This may possibly be a true back E.M.F., which, although large compared with that of an ordinary cell, is very small compared with that which has been supposed to exist in the arc."

It is to be remarked that Mr. Duddell's results do not conflict with Mrs. Ayrton's argument, which does not preclude the possibility of the existence of the back E.M.F. which he found. The figures found by Mr. Duddell, moreover, help to account for the one phenomenon which Mrs. Ayrton's states is not explained by the variations which she discusses.

[1] The so called negative resistance of the arc is the value obtained for $\frac{d\,V}{d\,A}$, which under certain conditions of the alternating measuring current is negative. Mr. Duddell's paper shows that, as under these conditions the power factor is not unity, $\frac{d\,V}{d\,A}$ does not represent the resistance of the arc.

Positive and Negative Carbon P.D.'s.—It is possible from the results of Mr. Duddell's experiments to calculate the distribution of potential across the arc. For the case for which we have given the data, this works out in round figures as shown in the following table.

TABLE XIX.

DISTRIBUTION OF POTENTIAL IN 11 M/M SOLID-SOLID ARC 3 M/M LONG, 10 AMPERES.

Back E.M.F. at positive carbon	17 volts	33 volts = positive carbon P.D.
Resistance drop at positive carbon = $1 \cdot 6 \times 10$ . .	= 16 volts	
Resistance drop through arc = $0 \cdot 4 \times 3 \times 10$ . . .	= 12 volts	12 volts = vapour P.D.
Resistance drop at negative carbon = $1 \cdot 2 \times 10$ . .	= 12 volts	6 volts = negative carbon P.D.
Forward E.M.F. at negative carbon	= −6 volts	
Total potential difference .	51 volts	

The variations in the positive carbon P.D. and the negative carbon P.D. with variations of current and length of arc have been studied by using a third search carbon in the arc. Mrs. Ayrton discusses this question at length, and finds that the positive carbon P.D. varies from 30 to 40 volts with a solid positive carbon, increasing with the length and decreasing with the current, and the negative carbon P.D. varies from 8 to 12 volts, decreasing with the current, but being practically independent of the length of arc. Coring the positive carbon reduces both the positive carbon P.D. and the vapour P.D. slightly, 2 to 3 volts altogether, and coring the negative carbon reduces the vapour P.D. about 2 volts, but scarcely affects the negative carbon P.D.

Hissing Arcs.—When the current through an arc of given length and with given carbons is increased, at a certain value the arc begins to hiss, and at the same time a drop of about 10 volts takes place in the P.D. This is shown in the curves in Figs. 86 and 87. The dotted portion of these curves indicates the beginning of the hissing state, and the final full portion at a lower voltage the continuation of the curves for hissing arcs. For a full explanation of the dotted portion the reader is referred to Mrs. Ayrton's book, Chapter X. The same effect is naturally produced if the current be kept constant and the arc length diminished below a certain value. Thus it will be seen from the curves in Fig. 86 that if the length of an 18-ampere solid-solid arc is diminished from 4 *m/m* to 2 *m/m* a hissing arc would be produced. Mrs. Ayrton was the first to give the explanation of this phenomenon, which she showed was produced by the crater becoming so large that it more than filled the end of the point of the positive carbon. Under these conditions air obtains access to the crater surface and the oxygen combining with the carbon causes the lowering of the P.D. The air is alternately sucked in and driven out, whence arise the hissing sound and the rapid fluctuations observable in the current. Under these conditions a mushroom may form on the tip of the negative carbon, as shown in Fig. 88.

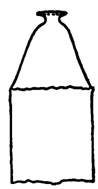


FIG. 88.—"Mushroom" on negative carbon.

Alternating Arcs.—The laws connecting the variables of alternating-current arcs have not been studied to nearly the same extent as those for direct-current arcs. As the study

of these laws is mainly of interest for the elucidation of the phenomena actually occurring in the arc, the simpler case presented by the direct-current arc is naturally more suitable for experiment. It is to be noted that the actual mechanism having once been fully explained in the case of the direct-current arc it would be a comparatively easy

FIG. 89.—Wave forms. Alternating arc: 3 *m/m*, 14·8 amps. Carbons: 13 *m/m* solid/13 *m/m* solid.

(*Outermost curve* = P.D. dynamo. *Middle curve* = current. *Innermost curve* = P.D. arc.)

matter to extend the explanation to other types of arc. Mention must be made, however, of a most valuable paper by Messrs. W. Duddell and E. W. Marchant[1] on the wave forms of alternating-current arcs which they studied by means of an oscillograph. This paper contains a large number of wave forms which show that the arc always distorts more or less the wave form of the applied E.M.F.

[1] *Journal of the Institution of Electrical Engineers*, Vol. XXVIII., p. 1, 1899.

FIG. 90.—Wave forms. Alternating arc: 3 m/m, 14·8 amps. Carbons: 13 m/m cored/13 m/m solid.

(*Outermost curve* = P.D. dynamo. *Middle curve* = current. *Innermost curve* = P.D. arc.)

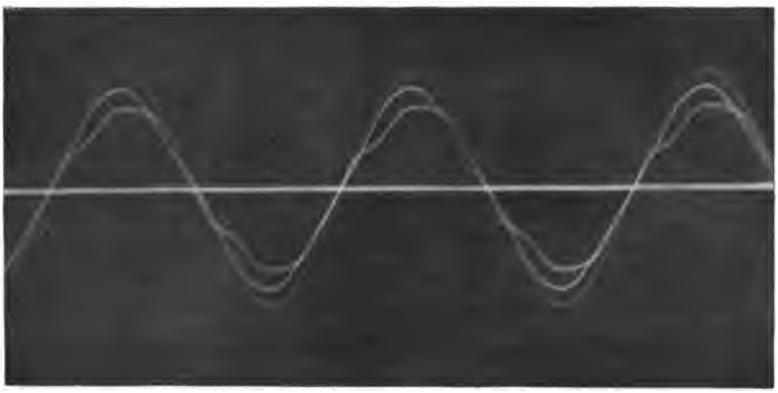


FIG. 91.—Wave forms. Alternating arc: 3 m/m, 14·8 amps. Carbons: 13 m/m cored/13 m/m cored.

(*Outermost curve* = P.D. dynamo. *Middle curve* = current. *Innermost curve* = P.D. arc.)

Some typical curves, kindly lent me by Mr. Duddell, for three different arcs are shown in Figs, 89, 90, and 91. Fig. 89 shows the distortion when both carbons are solid; Fig. 90 when one is solid and one cored; and Fig. 91 when both are cored. All three figures are for 14·8 amperes 3 m/m arcs. These figures show that the greatest distortion occurs with solid-solid arcs; with solid-cored and cored-cored arcs the distortion is much less, being least in the latter case. Both these latter cases are common in practice, the cored-cored arc being the most usual. With solid-solid arcs the power factor of the arc is about 0·7 to 0·9; with solid-cored or cored-cored arcs the power factor is always higher, and in the latter case is very nearly unity. The cored-cored arcs are also more stable.

Flame Arcs.—The flame arc being of quite recent introduction has naturally not yet given rise to much research. Some of the peculiarities in connection with flame arcs will be discussed in Chapter X., when the subject of flame lamps is considered. Apart from the fact that the flame arc offers in many respects special facilities for studying the various physical phenomena of the arc and verifying or extending the conclusions already deduced there is a very wide field for chemical investigation in this connection. The actual chemical phenomena occurring in the ordinary arc are still somewhat obscure; in the flame arc they are still more difficult to understand, and valuable theoretical and practical results are likely to follow from their fuller investigation.

CHAPTER IX

THE MANUFACTURE AND TESTING OF ARC LAMP CARBONS

Manufacture.

The modern arc lamp carbon is a highly specialised product, very different from the crude sticks of charcoal or rods cut from retort carbon which served as the electrodes for the earliest arcs. The manufacture of carbons being essentially a process which is more economical the larger the output it is not surprising that the industry is confined to a very few works, of which only one is situated in England. The great bulk of the carbons used in this country are manufactured abroad. The courageous attempt made by the firm to which the writer belongs to establish the industry in this country produced a cutting on the part of the foreign manufacturer, which resulted in three years in halving the price of carbons. Probably in no other country does the electrical engineer obtain carbons so cheaply as in England, and the price of ordinary carbons is so low that it scarcely forms a factor worth consideration in arc lighting.

The raw materials used in carbon making are gas-retort carbon, soot, and tar. All must be carefully selected to ensure only the purest material being used, and the soot and tar must be specially prepared to have a certain definite physical and chemical condition. Petroleum coke may be substituted for retort carbon, but the carbons thus

made are of inferior quality and burn much less steadily than retort carbons. The retort carbon is ground to a very fine powder and then mixed in the desired proportions with the soot and tar. The highest grade carbons contain only a small percentage of retort carbon; such carbons give more light and less residue, but burn rather more rapidly than those containing more retort carbon. On account of the longer burning hours the lower grade carbon is in more general use in England, though foreign users are more enlightened in this respect.

The mixture is well kneaded and then forced by hydraulic pressure through steel dies into long rods of the required diameter. When cored carbons are pressed a hole is left down the centre of the carbon, to be filled at a subsequent stage with the coring material. The rods are cut as they issue from the press into suitable lengths, generally about one metre, and these are tied up into bundles and packed upright into fireclay crucibles, in which they are baked to a temperature of about 1,500° C.

The baking operation is one of considerable difficulty, and must be carried out with great care. It is essential for the temperature to be raised very evenly and gradually to the full heat required, for the final temperature to be maintained sufficiently long to ensure the thorough baking of all the carbons, and for the cooling to be slow and steady. The process is generally carried out in specially constructed gas-fired furnaces, working on a continuous and pseudo-regenerative principle. In Fig. 92 is shown a diagrammatic view of the furnaces belonging to the General Electric Company at Witton; this type of oven was originally designed by the German engineer Meiser, and

is known by his name; it is an adaptation of the porcelain ovens designed by Escherisch.

The furnace consists of 36 chambers (1—36), arranged in two parallel rows of 18 along the length of the oven-house. The chambers are let into the ground and can each be covered with a firebrick lid held in an iron frame; each chamber, though forming, as it were, a separate oven, is only separated from its neighbours on either side by an open chequerwork wall which allows of free passage of the gases from one chamber to the next. Two smaller chambers (C1 and C2) connect the two rows, one at each end, and thus form a complete ring of ovens. On the outer side of the two rows of ovens run two flues (F1 and F2), which lead to the chimney and to which connection can be made from any desired oven. In between the two rows runs the gas canal (G), into which pass the gases from two gas producers (G1 and G2), and from which connection can be made through water-sealed connecting pipes to any oven. In the diagram the shaded ovens are supposed to be open; they are not playing any part in the burning of the fire, but are being filled with carbons to be baked or emptied of those already baked. The remaining chambers (Nos. 6 to 25) form the "furnace" for the time being; their lids are on and they contain carbons in various stages of baking. It will be seen that gas is being led from the central gas canal through the two pipes P1 and P2 into chamber No. 12. The air necessary for the combustion of this gas enters the series at chamber No. 5, which has its lid off, passing down into this chamber and thence through the chequer wall separating it from chamber No. 6 into the series of covered ovens; the air passes from one oven to the next till it

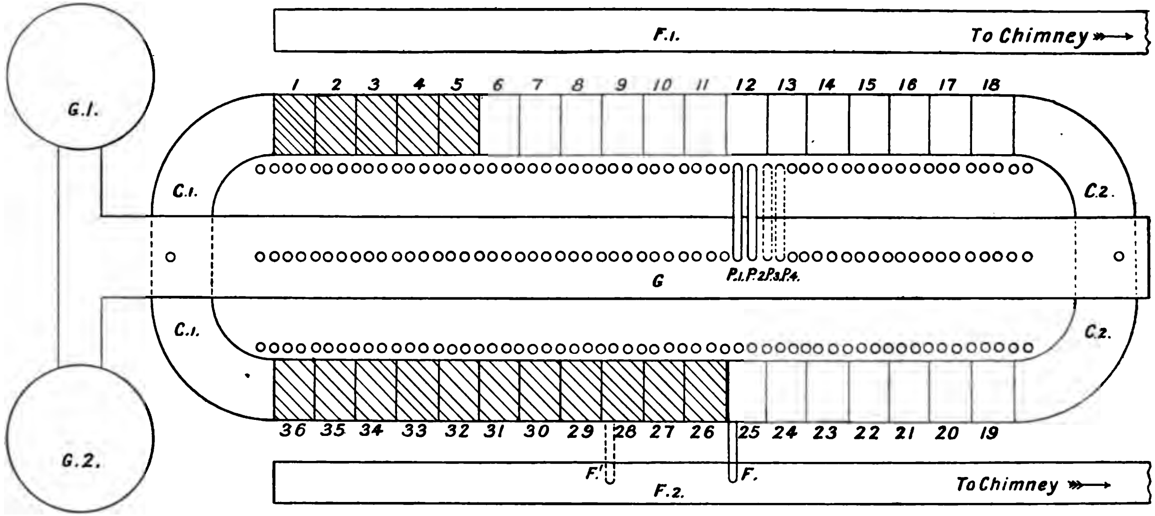


FIG. 92.—Diagrammatic plan of carbon-baking ovens. (Witton.)

reaches the gas, when the two burn together and the flue gases pass from chamber 12 to chamber 13 and so on to the last chamber which is closed (No. 25), from whence they are led to the flue by the connector F. It will be seen that the waste heat of the flue gases is utilised in heating up the carbons in chambers 13 to 25, and by the time the gases reach the flues they are cooled as far as possible consistent with the maintenance of a good chimney draught. The fire is kept burning in oven 12 until the desired temperature is reached; it is then "moved forward" by shifting the connecting pipe P1 into the position P3. After the fire has been long enough in this position P2 is shifted into the position P4. Thus the fire is continually moving round the ring of chambers, and two results of this will at once be noticed. In the first place the burning gases are only brought into play on carbons already nearly at the full temperature. In the second place the air for combustion has to pass over the baked carbons and whilst cooling them becomes itself heated nearly to the full temperature before combustion takes place. In this way a very intense heat is obtained with great economy and the perfectly regular heating up and cooling down of the carbons is effected in a simple manner. In Fig. 93 are shown curves taken with a thermo-electric thermometer which show the rise and fall of temperature inside and outside a pot full of carbons during the baking process. A little consideration will show that as the fire is advanced the number of chambers in the "front fire" becomes too small and the number in the "back fire" too great. After a certain time, therefore, more chambers are put in front by closing down the lids of Nos. 26 to 28 and removing the flue connection

from F to F′. The open wall between the last closed oven and the first open one is sealed; this is done by an iron plate sealed against the wall (on the side in the open oven), which is removed when the fire is lengthened. As the fire is lengthened in front it is simultaneously shortened behind

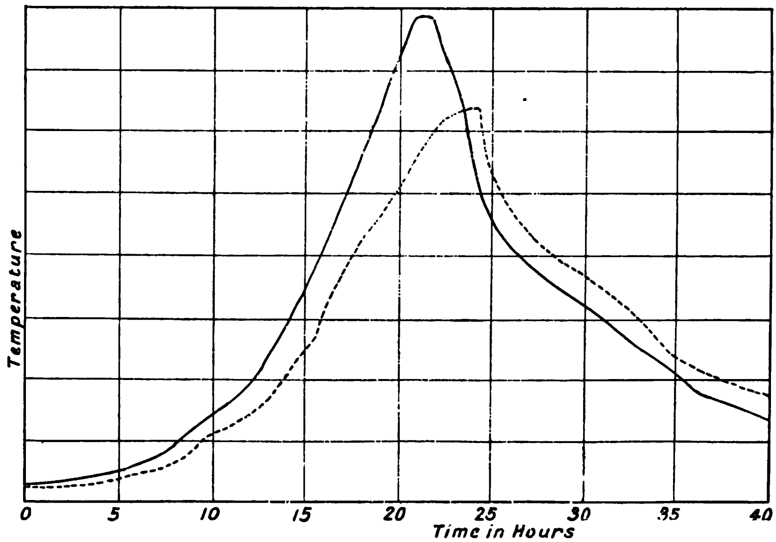


FIG. 93.—Rise and fall of temperature in baking carbons.
Full curve, temperature outside crucible. *Dotted curve*, temperature inside crucible.

by lifting the lids from chambers 6 to 8. Thus the series consists always of approximately the same number of ovens both before and behind the fire. It will be seen also that the fire moves steadily round the ring, and the baking operation is continuous day and night all the year round, being only interrupted when the furnace requires a more

thorough cleaning and repair than can be effected whilst it is in operation.

Baking processes have been devised in which the carbons are carried on trolleys slowly through a furnace maintained always at the full temperature, but the type of oven described above is certainly generally, if not exclusively, used.

The baked carbons are cut to the required length, sorted to pick out defective carbons (either crooked, cracked, or otherwise faulty), ground flat at one end, and pointed at the other. The cored carbons are then cored by squirting into the canal a mixture of finely ground carbon and concentrated potassium silicate. This mixture is forced in under considerable pressure, and must be made to completely fill the canal; the carbons are then heated to about 150° C. to thoroughly dry the core.

Carbons are made in all diameters from about 5 *m/m* to 24 *m/m* for ordinary arc lamps; for searchlight and lighthouse work carbons from 30 to 40 *m/m* in diameter are used, and these are often electrolytically coppered to increase the conductivity and diminish the rate of burning. Generally the diameters vary in millimetres, but for some special lamps intermediate diameters are used. The lengths vary according to the construction of the lamp and the number of burning hours desired, from 6 to 18 inches; flame carbons are made in lengths up to 30 inches.

The size of the core canal varies with the diameter of the carbon. The core canal in flame carbons is much larger than in ordinary carbons of the same diameter; this is in order to ensure the equal burning away of the flame material contained in the core and the surrounding solid

carbon envelope. The resistance of the core is very high compared with that of the surrounding carbon; flame carbons, on account of their small diameter and large core, have therefore a very high resistance per inch length, and in order to overcome the drop in volts that would consequently occur along the carbon, the carbons are often coppered, or more generally "metallic-cored" carbons are used. These have a metal wire inserted in the carbon which may either be in the core canal itself or in a separate canal running through the solid envelope. This wire is allowed to project for a short distance above the flat end of the carbon, where it is flattened out and bent down the side of the carbon, as shown in Fig. 94, so that in screwing up the carbon holder in the lamp direct contact can be made to the wire.

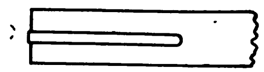


FIG. 94.—Butt end of metal-cored flame carbon.

The mixtures used for positive and negative carbons are different to ensure equal burning away of the two carbons: this might be directly attained by suitably choosing the diameters of the carbons, but the diameters which are paired in practice are not correct for this. As different users pair different diameters, one, for example, burning 20 *m/m* cored with 13 *m/m* solid, a second 18 *m/m* cored with 13 *m/m* solid, and a third 18 *m/m* cored with 12 *m/m* solid, it is naturally not possible to obtain exactly equal rates of burning in all cases.

TESTING.

The testing of carbons is a different matter to the testing of arc lamps, and the first thing of which to make certain in carrying out any test is that the lamps in which the

carbons are burnt are in perfect order. When the carbons are to be used on a particular circuit the tests should be made as nearly as possible under actual running conditions, but when it is only desired to compare the relative merits of different makes or qualities, it is more important to make the tests in lamps which regulate and feed as smoothly as possible, as it is desirable not to complicate the test results by defects introduced by the lamps themselves. For the same reason it is important to take precautions that the supply voltage and current are steady throughout the test. Bad burning results are bound to be obtained on a circuit on which the voltage regulation is defective. Carbons which are suitable for certain lamps may give much worse results in lamps of a different type; for this reason it is of importance, where possible, to use for testing purposes lamps of the same type as those in which the carbons are to be burnt. The differences with modern lamps are generally slight, but with some of the older lamps still in use may be considerable.

It must also be remembered that the conditions of the test should be as severe as the practical conditions. For example, almost any quality carbon will burn well when tested in a single direct-current lamp run off a 100-volt circuit with the necessary resistance in series. By testing two lamps in series on 100 volts, or five in series on 230 volts, the conditions are made much more severe, and faulty carbons which are apparently quite satisfactory under the easier test will soon show defects under conditions such as these. It need hardly be added that test results to be of any real value should be the average of a number of tests. Individual carbons of the same make and quality show

considerable variations, and these can only be eliminated by testing a fair number of carbons and averaging the results.

The most important tests to carry out on carbons are the following:—Rate of burning, amount of residue or "ash," steadiness of burning, and candle-power.

In making a test of the rate of burning the carbons should be both measured and weighed before and after the test. The result is most conveniently expressed by calculating for each carbon the rate of consumption in both millimetres and grammes per hour. From the figures obtained for the rate of consumption in millimetres per hour, the life of the particular pair of carbons can be calculated, and it can be seen whether the positive and negative will burn out evenly. Thus, for example, a pair of 18 *m/m* and 12 *m/m* twelve-inch carbons are found on test to burn at the rates of 12·2 and 11·8 *m/m* per hour respectively. Allowing for a length of $1\frac{1}{2}$ inches of the positive carbon to be left in the holder, the burning hours for this pair of carbons is $\dfrac{10{\cdot}5 \times 25{\cdot}4}{12{\cdot}2} = 21{\cdot}9$ hours and the length of negative carbon left unburnt will be approximately $1\frac{3}{4}$ inches. It must be understood that it is not always necessary for the carbons to burn at equal rates; thus, in one fairly common type of lamp a 13 *m/m* cored positive is burnt with a 13 *m/m* solid negative; under these conditions the positive burns nearly twice as fast as the negative, and the carbons are made to burn out evenly by using a 15 to 16 inch positive with an 8 to 9 inch negative. Numerous other combinations of unequal length carbons are common.

The test of rate of consumption should always last at

least ten hours, as otherwise the irregularities which occur during the first hour whilst the carbons are burning to shape vitiate the final result. The test should be carried out with the globe on the lamp; this should be carefully cleaned before the test, and after the test all the residue which has been deposited in the globe should be brushed out with a small soft brush and weighed. It is best to calculate from the known weights of residue formed and carbon burnt the percentage of the weight burnt which is deposited as residue, as then different tests can be compared, *e.g.*, the residue obtained from a pair of 16 *m/m* and 10 *m/m* carbons burning with 8 amperes compared with that from a pair of 22 *m/m* and 15 *m/m* carbons burning with 15 amperes; or the residue from a ten-hour test compared with that from a fifteen-hour test. Suppose, for example, in a ten-hour test on 18 *m/m* and 12 *m/m* carbons 0·675 grms. of residue are deposited, and it is found that 44 grms. of the positive and 19 grms. of the negative have been consumed, the total weight burnt is 63 grms., and the residue as a percentage of the weight burnt is 1·07. The residue is often spoken of as "ash," but it is not a true ash since it consists for the most part of unburnt carbon.

In Table XX. are given the average test results on a number of carbons of different diameters burning with the currents most commonly used in practice for these sizes. The carbons are all of the General Electric Company's "Apostle" quality, which is a "retort" carbon, *i.e.*, a carbon containing a comparatively high percentage of retort carbon. In Table XXI. are given the average test results on a number of 18 *m/m* and 12 *m/m* carbons of different makes and qualities. Three of the sets are test

results on "retort" carbons, and the other three on "soot" carbons, *i.e.*, carbons composed chiefly of soot.

TABLE XX.

AVERAGE TEST RESULTS OF APOSTLE CARBONS OF DIFFERENT DIAMETERS.

Five lamps in series on 230 volts direct-current.

Size.	Current.	Consumption in m/m per Hour.			Residue as Percentage.
		Positive.	Negative.	Total.	
	Amperes.				
16 m/m cored and 10 m/m solid .	8	13·3	13·8	27·1	0·90
18 ,, 12 ,, .	10	12·2	11·3	23·5	0·73
20 ,, 13 ,, .	12	11·7	11·7	23·4	0·88
22 ,, 14 ,, .	15	11·9	11·7	23·6	1·26
22 ,, 15 ,, .	15	11·1	10·3	21·4	1·21

TABLE XXI.

AVERAGE TEST RESULTS OF CARBONS OF DIFFERENT MAKES AND QUALITIES.

Carbons: 18 m/m cored positive and 12 m/m solid negative.
Circuit: 10 amperes; 5 lamps in series on 230 volts direct-current.

Make.	Mark.	Quality.	Consumption in m/m per Hour.			Residue as Percentage.
			Positive.	Negative.	Total.	
Conradty .	Krone .	Soot .	14·0	16·0	30·0	0·32
,, .	Noris .	,, .	14·4	16·4	30·8	0·35
G. E. Co. .	Nubia .	,, .	13·0	13·3	26·3	0·47
Conradty .	C . .	Retort	12·8	11·3	24·1	1·86
Schiff .	G. .	,,	12·1	12·0	24·1	1·45
G. E. Co. .	Apostle	,,	12·1	11·4	23·5	0·80

It will be seen from Table XX. that the ash is usually higher the larger the current. This is due probably to the greater ease with which small particles of carbon can get

loosened and fall off under such conditions. From Table XXI. it can be seen that the rate of consumption is higher but the residue lower with soot than with retort carbons. Soot carbons have other advantages in addition to the smaller residue, to which reference will be made presently.

In Table XXII. are given some specimen test results of carbons in alternating-current lamps. As some users take two cored carbons and others an upper cored and a lower solid carbon for this purpose, examples of both sorts are given in the table. In some cases also a special quality carbon is supplied for alternating-current circuits in order to increase the burning hours, the carbon containing a higher percentage of retort and having a smaller core canal; examples of tests on this quality are also given; it will be noted that the residue is higher with these carbons.

TABLE XXII.

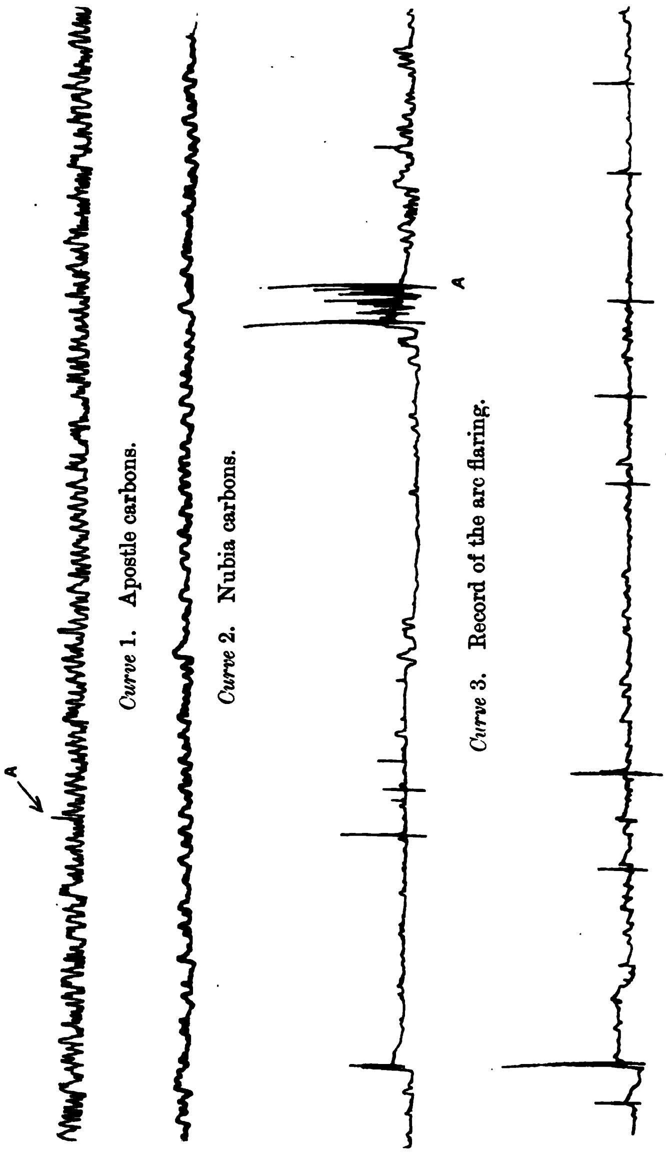
CARBONS ON ALTERNATING-CURRENT.

Carbons: both 15 *m/m* diameter.
Circuit: 15 amperes; 3 lamps in series on 105 volts 50 ∿.

Particulars of Carbons.	Consumption in *m/m* per Hour.			Residue as % of Weight burnt.
	Upper.	Lower.	Total.	
General Electric Co., Apostle A. C., Upper cored, Lower cored . .	13·2	14·7	27·9	2·5
General Electric Co., Apostle (Ord'y), Upper cored, Lower cored . .	14·9	16·8	31·7	1·1
General Electric Co., Nubia, Upper cored, Lower cored . .	17·2	20·1	37·3	1·0
Conradty, Mark W. C., Upper cored, Lower cored . .	14·3	15·1	29·4	2·0
General Electric Co., Apostle, Upper cored, Lower solid . .	13·5	14·4	27·9	1·6
Conradty, Mark W. C., Upper cored, Lower solid . .	11·9	12·6	24·5	2·2
General Electric Co., Nubia, Upper cored, Lower solid . .	15·7	16·0	31·7	0·9

The rate of consumption and the residue are both affected by the supply conditions. Too high a current increases both, as also does too high an arc voltage; unsteady voltage has always the effect of increasing the amount of residue, and also generally alters the relative rates of consumption of the carbons.

The steadiness of burning can only be observed by using a recording ammeter or voltmeter, or preferably both, throughout the test. It is practically useless to attempt to judge the steadiness by observing the arc or its image, firstly because carbons may burn very well for a time and then very unsteadily, and secondly because a comparison of this kind, depending upon memory, is to all intents and purposes useless. Of course in the rare case of very unsteady burning throughout the test observation alone may be sufficient. The writer uses always a recording ammeter connected in series with the arcs, and a recording voltmeter connected across each arc in turn. These instruments are specially constructed with very freely swinging needles, so that any flicker should be exaggerated on the curve. Some experience is necessary to distinguish on the curve irregularities due to variations in the supply voltage, or sticking in the lamp feeding mechanism, from those due to imperfections in the carbons. It may also be remarked that it is important to see that the carbons are properly centred in the lamps, as bad centring leads to unsteady burning. In Fig. 95 are shown four specimen recorder curves; one of these (Curve 1) is for Apostle, and one (Curve 2) is for Nubia carbons. The slight rises and falls in these curves show the feed of the lamp, which it will be seen is rather more regular with the Nubia (soot)



Curve 1. Apostle carbons.

Curve 2. Nubia carbons.

Curve 3. Record of the arc flaring.

Curve 4. Petroleum coke carbons.

FIG. 95.—Recorder curves: various carbons, open arcs.

carbons. At A in the Apostle curve is a slight flicker of the arc; this would be scarcely visible as an alteration of the light given by the lamp. In Curve 3 is shown the record of a bad "flare" taking place in the arc. Curve 4 is for a petroleum coke carbon, which it will be seen burns with constant flickering; on observing the light given by these carbons a constant flicker was noticeable, as if the lamp were vibrating rapidly. These carbons were sent

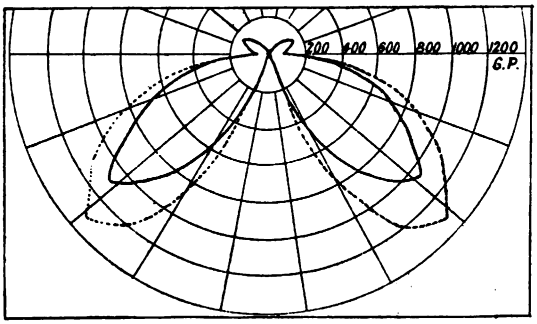


FIG. 96.—Vertical distribution curves. Open arc. *Full curve,* Apostle (retort) carbons. *Dotted curve,* Nubia (soot) carbons.

to the writer as samples of high quality carbons, the reason being that in outward appearance they were very attractive, which is characteristic of petroleum coke carbons.

Very few engineers go to the trouble of testing the amount of light given by the carbons they use; this is a laborious matter, and there seems to be a general impression that all carbons under similar conditions give the same amount of light. That this is quite incorrect is shown by the distribution curves given in Fig. 96, which

show the distribution with Apostle and Nubia carbons respectively under the same burning conditions. These curves were obtained by the National Physical Laboratory. The carbons tested were 18 *m/m* cored and 12 *m/m* solid, burning at 10 amperes and 48 volts. The results of the test are summarised in Table XXIII.

TABLE XXIII.

	Arc Length *m/m.*	Consumption in *m/m* per Hour.			Resistivity, Ohm-centimetre.		Density.		M.S.C.P.	W./M.S.C.P.
		+	–	Total.	+	–	+	–		
Apostle .	1·1	14	13	27	0·073	0·063	1·40	1·50	346	1·39
Nubia .	1·3	16	16	32	0·090	0·081	1·275	1·32	440	1·09

From these figures one can calculate the saving to be effected by using high-grade carbons. At present prices a pair of 18 *m/m* and 12 *m/m* 12-inch Apostle carbons costs 1·06*d.*, and a pair of Nubia carbons 1·58*d.* Allowing the carbons to burn until 2 inches of each are left, the Apostle carbons will burn for 19 and the Nubia for 16 hours.[1] The candle-hours given by the Apostle carbons is therefore 6,576, and by the Nubia carbons 7,040, say 6,600 and 7,000 respectively. The cost of carbons for 10,000 candle-hours is consequently, with Apostle carbons, 1·61*d.*, and with Nubia carbons 2·25*d.* The cost of current is obtained from the fact that the Apostle carbons require 1·39 watts per candle, and therefore 13·9 units for 10,000 candle-hours, and the Nubia carbons require 1·09 watts per candle, and therefore 10·9 units per 10,000 candle-hours. The

[1] It is to be noted that the voltage in these tests is higher than that usual in practice, but the comparison is based on the result of this test

saving effected for 10,000 candle-hours by using the soot carbons is set out in Table XXIV.

TABLE XXIV.

Cost per Unit.	1*d.*	2*d.*	3*d.*	4*d.*	5*d.*	6*d.*
	d.	*d.*	*d.*	*d.*	*d.*	*d.*
Total cost Apostle carbons (retort)	15·51	29·41	43·31	57·21	71·11	85·01
Total cost Nubia carbons (soot)	13·15	24·05	34·95	45·85	56·75	67·65
Saving with Nubia carbons	2·36	5·36	8·36	11·36	14·36	17·36

Stated shortly, there is a saving for 10,000 candle-hours of 2½*d.* at a penny per unit, and an additional saving of 3*d.* for every extra penny per unit. As, however, most engineers are not in a position to reduce the number of their lamps, we can put the case in another way, by saying that the use of the higher grade carbons with current at 2*d.* per unit will give an increase of, in round figures, 25 per cent. in the light, with an increase of only 4 per cent. in the cost.

The testing of carbons for use in enclosed lamps calls for little special comment. The rate of consumption is determined in the same way as with open-type carbons. It is more important with enclosed carbons that the residue should be small, as it is deposited as a film on the surface of the globe and consequently obscures the light. For this reason enclosed carbons are always made almost wholly of soot. The weight of residue may be determined by weighing the inner globe before and after the test. It

is often the case, however, that the deposit may be heavier in one case than another but yet be less opaque, and so obscure less light; it is a better plan, therefore, to keep the inner globes for reference, closing both ends with a sheet of paper gummed to the glass so as to prevent access of dust. The relative opaqueness of the deposit with different carbons can then be compared at any time. The rate of burning depends to a very large extent on the degree to which air is prevented from leaking into the inner globe; care must therefore be taken to see that the globes are properly fastened, and that the carbons are correct in diameter. Enclosed carbons should not vary more than 0·1 *m/m* from the nominal diameter, and some users specify closer limits even than this. Open-type carbons can vary 0·2 to 0·3 *m/m* above or below the nominal diameter without appreciably affecting the burning results, and unless the carbon-holders happen to be small and do not admit of much adjustment, variations of diameter are unimportant.

Some typical test results for enclosed carbons of different makes are given in Table XXV., and in Fig. 97 is shown a recorder-curve for an enclosed lamp. The curve is very steady, except where the kicks occur; these are due to the feed of the lamp which, like that of most enclosed lamps, is much less smooth than in open-type lamps.

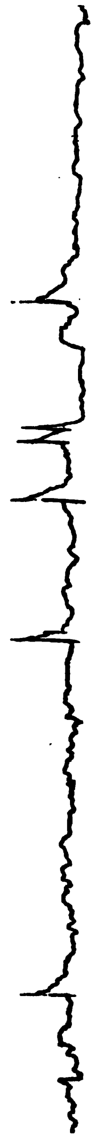


Fig. 97.—Recorder curve: enclosed arc.

TABLE XXV.

TEST RESULTS FOR ENCLOSED LAMPS.

Carbons.			Circuit.			Consumption in m/m per Hour.			Residue as % of Weight burnt.
			Volts	Amps.		Upper Carbon.	Lower Carbon.	Total.	
General Electric Co.,	$\frac{11\ m/m}{11\ m/m}$,	both solid	110	5	=	1·51	0·56	2·07	0·23
Schiff	"	"	"	"	=	1·50	0·58	2·08	0·21
Siemens	"	"	"	"	=	1·40	0·69	2·09	0·24
Conradty	"	"	"	"	=	1·71	0·83	2·54	0·20
General Electric Co.,	$\frac{13\ m/m}{13\ m/m}$,	"	105	6	=	2·20	0·93	3·13	—
Conradty	"	"	"	"	=	2·30	1·22	3·52	—
General Electric Co.,	"	both cored	110	7·5	~	0·92	1·03	1·95	—
Schiff	"	"	"	"	~	1·29	1·33	2·62	—

It must be remembered that the actual results obtained vary greatly according to the tightness of the enclosure, so that very concordant results cannot be expected. This is especially the case with alternating-current tests, as the alternate heating and cooling draws air into the enclosure if this is not very tightly closed. The chief source of trouble lies in the ring through which the upper carbon slides; this must of course be a sufficiently easy fit to allow the carbon to slide freely, but if it is too large the rate of burning will be greatly increased and at the same time the admission of air into the globe will cause the arc to burn very unsteadily, and to form a very heavy deposit. The figures given in Table XXVI. below show how great an effect the size of this ring has; the three tests were all made on the same pair of carbons.

TABLE XXVI.

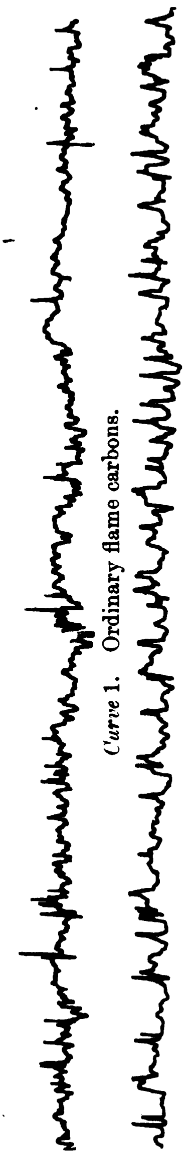
EFFECT OF DEGREE OF ENCLOSURE.

11 m/m cored carbons on 100 volts, 5 amperes alternating-current.

	Consumption in m/m per Hour.		
	Upper.	Lower.	Total.
Globe-cap ring 0·4 m/m bigger in diameter than the carbon . . .	1·69	1·69	3·38
Globe-cap ring 0·6 m/m bigger in diameter than the carbon . . .	7·52	6·23	13·75
Globe-cap ring 0·7 m/m bigger in diameter than the carbon . . .	10·75	9·25	20·00

It is sometimes found when enclosed lamps are first switched on that the lamp is continually "pumping," *i.e.*, the arc going out and restriking in fairly rapid succession. This is due to the presence of moisture either in the carbons or the globe, and consequently occurs either when the lamp is trimmed with carbons which have been kept in stock in a moist place, or when the lamp is restarted after standing idle for some time in a moist atmosphere, especially if the enclosure is not very good.

The testing of flame carbons requires more care than the testing of ordinary carbons. In addition to determining the rate of consumption it is most important to see whether the carbons burn away at even rates, as in most flame lamps they are not fed independently. It will generally be found that if the carbons burn unevenly, one will burn so that it projects somewhat further below the economiser than the other. In consequence this carbon is brought into an atmosphere containing a greater percentage of oxygen, as will be seen at once on reference to



Curve 1. Ordinary flame carbons.

Curve 2. Metal-cored flame carbons.

FIG. 98.—Recorder curves: flame arcs.

Fig. 83, p. 206, and begins to burn at a quicker rate. A position of equilibrium is thus eventually attained at which the carbons burn at equal rates, but owing to one carbon being longer than the other and the arc no longer properly situated relatively to the controlling magnetic field and the economiser, it will be found that the arc burns very unsteadily. Flame carbons vary very greatly in design and composition, according to the construction of the lamp in which they are used. In some lamps both carbons require to be cored with flame-producing material, in others only the positive carbon is so cored, and the size of the core canal varies greatly. Some of the more important differences will be referred to in the next chapter. It is sufficient here to emphasise the fact that the carbons must always be tested in lamps of the same make as those in which they are to be used, or in lamps which it is known burn with the same type of carbons. It is most important also to see that the adjustments of the lamps are correct, and that they are running at the correct voltage and current, as if the carbons burn too low

or too high in the economiser they will not burn properly, as they will not be burning in an atmosphere of the correct composition.

It is of no importance to determine the amount of residue with flame carbons. This is always high, and the amount which accumulates in the globe depends practically only on the efficiency of the ventilation provided in the lamp. The deposit is specially high with metal-cored carbons when zinc wires are used. Partly for this reason brass wire is often used instead of zinc, but this has the disadvantage that the deposit is then brown instead of pure white. The steadiness of the recorder curve is of importance. This is never so good with flame carbons as with ordinary carbons in the present state of the art, though doubtless the results will improve as this type of arc lamp becomes more generally used. Some typical flame-carbon records are shown in Fig. 98, and in Table XXVII. are given examples of test results. The fuller explanation of the different types of carbons tested is given in Chapter X., p. 265, but attention may be here drawn to the fact that the rate of burning is increased when both carbons contain flame-producing material in their cores, and is then naturally higher when the positive has a large core canal. The rate of burning depends very greatly on the adjustment of the lamp, a small difference in the average level of the arc making a large difference in the rate of burning. Thus, for example, with a pair of Conradty carbons altering the average level of the arc by about 5 *m/m* altered the rate of burning from 78·4 to 91·3 *m/m* per hour. In the same way the shape of the economisers in different lamps affects the rate of burning greatly.

Table XXVII.

Test Results of Flame Carbons.

Conditions of Test.	Positive Carbon.	Negative Carbon.	Total m/m per Hour.
Direct-current, 10 amp., 2 lamps on 100 volts. Excello lamps. Metal cored carbons.	8 m/m large core: flame - cored. Nubia.	7 m/m small core: ordinary-cored. Nubia.	85·1
	8 m/m small core: flame - cored. Nubia.	7 m/m small core: flame - cored. Nubia.	88·9
	8 m/m large core: flame - cored. Nubia.	7 m/m small core: flame - cored. Nubia.	90·7
	8 m/m large core: flame - cored. Conradty, 104.	7 m/m small core: ordinary-cored. Conradty, 105.	91·3
	8 m/m small core: flame - cored. Siemens.	7 m/m small core: flame - cored. Siemens.	89·5
Direct-current, 10 amp., 2 lamps on 100 volts. G. E. Co. lamps. Coppered carbons.	9 m/m large core: flame - cored. Nubia.	8 m/m small core: ordinary-cored. Nubia.	67·9
	9 m/m small core: flame - cored. Nubia.	8 m/m small core: flame - cored. Nubia.	68·9
Direct-current, 10 amp., 2 lamps on 100 volts. G. E. Co. lamps. Plain carbons.	9 m/m large core: flame - cored. Nubia.	8 m/m small core: ordinary-cored. Nubia.	82·5
	9 m/m small core: flame - cored. Nubia.	8 m/m small core: flame - cored. Nubia.	83·1
	9 m/m large core: flame - cored. Nubia.	8 m/m small core: flame - cored. Nubia.	92·5
Alternating-current, 10 amp., 1 lamp on 55 volts. Excello lamps. Metal cored carbons.	8 m/m small core: flame - cored. Nubia.	8 m/m small core: flame - cored. Nubia.	67·0
	8 m/m small core: flame - cored. Schiff.	8 m/m small core: flame - cored. Schiff.	58·9
	8 m/m small core: flame - cored. Conradty, 70.	8 m/m small core: flame - cored. Conradty, 70.	65·2
	8 m/m small core: flame - cored. Siemens.	8 m/m small core: flame - cored. Siemens	65·4

The diameter of flame carbons is a matter of importance, as small differences in diameter may affect the relative rates of burning. Generally speaking, the limits of variation should be about the same as for enclosed carbons. On account of the numerous causes which may affect the results of tests on flame carbons it is generally best to test at least two pairs of carbons at the same time in two lamps in series. If any defect is found the carbons can be interchanged from one lamp to the other half way through the test, and in this way it is generally possible to distinguish at once defects due to the carbons from those caused by faulty adjustment of the lamps, etc.

There are other characteristics for which carbons may be examined or tested, such, for example, as straightness, freedom from cracks, etc. The straightness can easily be examined by rolling the carbons along a flat table and observing whether there is any "daylight" between the carbon and the table. Except that they prevent good centring of the arc, bent carbons are no disadvantage. It will be understood, therefore, that the longer the carbons the more important it is that they should be straight. In the case of flame carbons, however, as these generally are fed through two guide holes quite close to the arc, straightness is in reality less important. Nevertheless a not unnatural prejudice exists against crooked carbons of all kinds. In the same way a prejudice exists against cracked carbons. The writer has frequently made tests on very badly cracked carbons but has never found the slightest effect produced on the steadiness of burning, rate of consumption, etc., unless the crack was so deep as to extend right through to the core of the carbon. One of the

leading carbon manufacturers even states that cracked carbons are to be preferred, as the cracks indicate thorough baking.

Carbons may be tested for density, specific gravity, porosity, ash and resistivity, etc., but these tests are mainly of interest to the manufacturer. The *density* is the weight of the carbon divided by its external volume, the *specific gravity* is the weight divided by the true volume, *i.e.*, the external volume less the volume of the pores, and the *porosity* is the percentage of the external volume which is occupied by the pores. From the figures obtained for the specific gravity and density one can tell approximately the percentage of soot in the carbon, the density being lower the higher the percentage of soot. In the same way the resistivity is higher the greater the percentage of soot. This is well illustrated by the figures already given in Table XXIII. from the National Physical Laboratory test. In Table XXVIII. these are rearranged to show the variation more clearly, the percentage of soot increasing from Apostle negative to Nubia positive.

TABLE XXVIII.

Quality.	Density.	Resistivity, Ohm-centimetre.
Apostle negative (least soot)	1·50	0·063
,, positive	1·40	0·073
Nubia negative	1·32	0·081
,, positive (most soot)	1·275	0·090

It may be here mentioned that though it is frequently stated that the core in the positive carbon keeps the arc central and steady because it is lower in resistance than

the surrounding carbon and so keeps the current in the centre, this is quite erroneous. The core is always very much higher in resistance than the surrounding solid carbon and is often almost infinite in resistance. The core keeps the arc centralised because the potassium silicate in it is easily volatilised, and when volatilised gives rise to an arc of lower resistance than that formed by the volatilisation of carbon. For the same reason the materials volatilised from the cores of flame carbons so lower the resistance of the arc, especially in the immediate neighbourhood of the positive crater, that an arc ten to fifteen times the length of an ordinary arc is maintained with the same voltage.

Testing the chemical composition of carbons, especially of flame carbons, is a matter of importance to the carbon manufacturer but only of slight interest to the user of arc lamps, who is concerned with the results obtainable and not the means used to attain them. It may be mentioned here, however, that the materials in general use in flame carbons for producing the flame are;—calcium fluoride for yellow light, cerium oxide for white light, and strontium fluoride for red light. The proper mixing of these materials and their purity are matters of the first importance in the manufacture of high-grade flame carbons. There are many other compounds which can be used, and it is possible that great developments may take place in the future in the art of producing flame arcs, since the enormous field which has been opened up is only partially explored.

CHAPTER X

ARC LAMPS

It is not proposed in the present chapter to make any attempt to describe the mechanisms used in commercial arc lamps to maintain a steadily burning arc. The number of these is too great for the inclusion of a detailed description of each in a book of this scope, and the selection of individual examples would be unfair since it cannot be said of any particular make of lamp that it is really superior to its competitors. Accuracy of workmanship and care in adjustment go far more to the making of a good arc lamp than the selection of any particular method of control. The general principles utilised to control the burning of the arc will be briefly described, and the three leading types of arc lamps, viz., open arcs, enclosed arcs and flame arcs, will then be considered from the point of view of their efficiency as sources of artificial light.[1]

Methods of Regulation.

The mechanism in an arc lamp has to perform two main functions, namely, striking the arc and keeping the arc length constant by feeding the carbons together as they burn away. In the simplest form of arc lamp, the hand-fed

[1] The subject of arc lamp mechanisms has moreover been dealt with very fully in a book on "Electric Arc Lamps," by J. Zeidler, quite recently published (1908) by Messrs. Harper and Bros.

lamp, these operations are carried out by the person controlling the lamp by turning a handle which separates the carbons or brings them together. By turning this in one direction the carbons are brought towards one another until they touch: the handle is then turned in the opposite direction, thus separating the carbons and striking the arc. The correct arc length having been obtained the arc is allowed to burn steadily, the handle being occasionally turned to bring the carbons together so as to correct for the lengthening of the arc due to the carbons burning away. An arc lamp has to perform these operations automatically: in addition it is necessary that the mechanism should vary the length of the arc in such a way as to compensate for slight variations in the current and voltage due to irregularities in the supply voltage, irregularities in the carbons, or unsteady burning in any one of a number of lamps connected in series. Finally, where a number of lamps are burnt in series, the regulating mechanism must be capable of switching in a resistance equivalent to the resistance of the lamp should the arc go out for any reason, such, for example, as the carbons burning away or the lamp refusing to feed.

The methods used for control in all modern lamps except one are electro-magnetic: in the one exception the feed and regulation are controlled by the contraction and expansion of a wire traversed and heated by the main current. The electro-magnetic methods of control are obtained by utilising the attractive action of a solenoid on an iron armature. The armature is connected through the lamp mechanism to the carbons and by its movements regulates the arc. The solenoid may be wound with fine wire and connected in

parallel with the arc, in which case it forms a *shunt* coil; or it may be wound with thick wire and connected in series with the arc forming a *series* coil; or two solenoids, one shunt wound and one series wound, may be used, in which case the lamp is said to be *differentially* controlled.

These three principles of control are illustrated diagrammatically in Fig. 99. The feeding mechanism shown in this figure is what is known as the brake wheel mechanism, one of the simplest and most satisfactory types. The two carbons are suspended from a wheel W and are so balanced that when this wheel is free to rotate the carbons are brought together by gravity. When the wheel W is rotated in the direction P the carbons are drawn apart, and when it is rotated (or allowed to rotate freely) in the direction Q the carbons are brought together. The movements of this wheel are controlled by a brake B attached to a lever L carrying the armature A which is attracted by the controlling solenoids. If the lever L is moved in the direction P it causes the brake B to grip the wheel and turn it in this direction, thereby separating the carbons. When the lever is moved in the direction Q the first action is to turn W in the same direction, but after a short movement the hold of the brake on the wheel is released and the wheel is set free to turn as far as necessary in the direction Q.

In Fig. 99, *A*, the movements of the lever L are shown controlled by a shunt solenoid S_1. The carbons being normally held apart owing to the position taken by the lever L when there is no pull on the armature A, there will be full pressure on the solenoid when current is switched on. The armature A is consequently pulled down, the

brake B released, and the carbons feed until they touch: the potential difference across the shunt coil thereupon falls to zero, the armature A is released, and the lever L rises causing the brake B to clutch the wheel, turn it and strike the arc. When the arc is struck there is again a P.D. across the solenoid, and again, therefore, a pull on the armature A. The lever L will therefore finally attain a

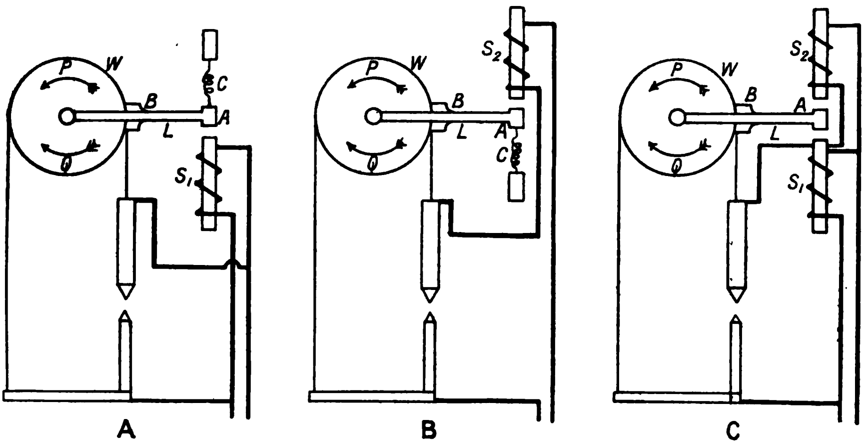


FIG. 99.—Principles of arc lamp control.
A, shunt control. *B*, series control. *C*, differential control.

position of rest in which there is a balance between the magnetic pull on A and the other forces acting on the lever. As the carbons burn away and the arc becomes longer the P.D. across the solenoid will rise and the lever be pulled downwards, bringing the carbons nearer together. After a certain amount of movement the wheel is set free and a slight feed of the carbons takes place, after which the same cycle of operations is repeated. Slight variations in current or potential difference during burning are regulated by the

up and down movements of the lever without any actual feeding (due to release of the brake) taking place.

In Fig. 99, *B*, the movements of the lever L are controlled by the series solenoid S_2. The details of the action need not be again explained since they are precisely similar to those already described, with the difference that the action of the solenoid is to *separate* the carbons instead of to bring them together. The carbons must, therefore, normally rest in contact or else the arc could not be struck. It will be seen that as the carbons burn away and the current falls the solenoid S_2 is weakened and allows feeding to take place.

The differential control shown in Fig. 99, *C*, is simply a combination of the two methods already described, the pulls of the two solenoids S_1 and S_2 being so balanced that the arc is maintained at the correct length. It is clear that in this case the normal position of rest for the carbons can be either in contact or apart, since in the one case the series coil, and in the other the shunt coil, would cause the arc to strike.

As has been already mentioned the magnetic control can be used to bring into action any suitable feeding mechanism. The principle of the brake mechanism described above is used with various modifications in a large number of lamps. In other lamps the carbons are fed together by a clockwork mechanism actuated by the weight of the carbons and released by the movements of the armature controlled by the regulating solenoids. In many enclosed lamps the mechanism is still more simple, the upper carbon alone being movable. This carbon slides through a clutch which holds the carbon fast when in one position but allows

it to slide freely downwards when in a second position: the movements of the clutch are, as before, magnetically controlled. In some lamps the mechanism is a motor mechanism, the magnetic solenoids bringing about the rotation of a small motor which winds the carbons together or apart as required.

It is desirable to note carefully the difference between the regulation of the arc and the feeding of the carbons. It is necessary in most cases that the lamp mechanism shall be capable of slightly lengthening or shortening the arc to take up small and quick variations in current and voltage without allowing the carbons actually to feed. This is effected, as already explained, with the brake mechanism by the small movements of the brake wheel before the brake is released. Similarly in clockwork mechanisms the regulating lever can control the length of the arc within certain limits before it releases the feeding gear. If this were not the case a slight temporary rise in voltage would cause the carbons to feed, and when the voltage had returned to the normal the arc would be necessarily too short, and would burn badly until the carbons had burnt away sufficiently to bring the arc back to its normal length.

Distribution of Light.

It is fairly common practice when comparing arc lamps to base the comparison on the mean *lower hemispherical* candle-power. Two reasons are generally advanced to justify this practice; first, that with most arc lamps so little light is given in the upper hemisphere that it may be neglected, and second, that for the class of lighting for

which arc lamps are used, light given above the horizontal is of little or no value. Neither reason, however, really justifies this habit, which is strongly to be deprecated. As a matter of fact, with arc lamps, almost more than with any other type of electric lamp, it is most desirable to know the mean spherical candle-power and the distribution curve, because they are used for lighting large open spaces where the calculation of the illumination that will be produced is comparatively simple when these factors are known.

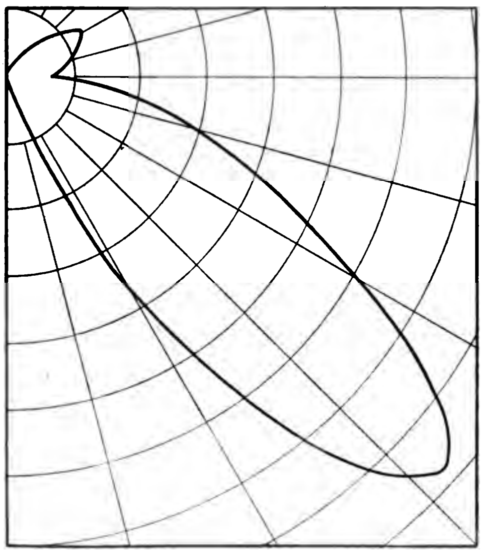


FIG. 100.—Vertical distribution curve. Open type arc. Direct-current.

Distribution curves for arc lamps vary very greatly on account of the very variable conditions under which the arcs may be burning. Thus differences in the diameters of the carbons for a given current, in their quality and in the design of the lamps all affect the shape of the distribution curves. It is not possible, therefore, in the present case to do more than show the typical shapes of these curves for different sorts of arcs.

Distribution curves for an ordinary open arc have been given already in Chapter IX., but the typical shape of the curve is reproduced in Fig. 100.[1] It will be seen that the amount of light radiated above the horizontal is practically negligible compared with that radiated in the lower hemisphere. This and the peculiar butterfly shape of the distribution curve renders the open arc particularly suitable for the lighting of streets and open spaces. In the first place, any light radiated above the horizontal is in such cases useless unless the lamps are provided with suitable shades or reflectors to divert it downwards again, a process necessarily involving loss by reflection. Secondly, it is desirable, as is here the case, that the maximum candle-power should be at an angle of about 45° with the horizontal, so that the more distant objects may be as brightly illuminated as those in the neighbourhood of the lamp. When, however, the way in which this peculiar distribution curve is formed is considered it will be seen that what appears at first sight an advantage is in reality one of the drawbacks of the open arc as a source of light.

The light from an open arc may be divided into five parts: (1) the light from the crater, (2) the light from the white hot tip of the negative carbon, (3) the light from the red hot end of the positive carbon, (4) the light from the red hot end of the negative carbon, and (5) the light from the arc itself. Of these the first two are the most important. Since the light from the crater is necessarily all thrown in the downward direction it is obvious that the

[1] In this, as in all the other distribution curves given in this Chapter, only one half of the curve is shown, the other half, when the arc is properly centred, being exactly similar.

small part of the distribution curve in Fig. 100 above the horizontal is due to the light from the white tip of the negative carbon together with the three other sources named. These four sources being also visible from below the horizontal (the white tip of the negative only partially), a similar curve drawn below the horizontal would give approximately the distribution of light from all the sources except the crater. It is clear, therefore, that the bulk of the light is derived from the crater of the positive carbon. It has been clearly proved by Mr. Trotter that, if the negative carbon were removed so that the whole of the crater was visible when viewed from any direction, the candle-power in any given direction would be proportional to the apparent area of the crater when viewed from that direction, *i.e.*, to the actual area multiplied by the cosine of the angle between the given direction and the perpendicular to the crater.[1] This is a natural consequence of the law of cosines given in Chapter III., p. 35. The distribution curve under these circumstances would be a circle A B C, Fig. 101, with one end of its vertical diameter on the crater. The fact that this distribution curve is not obtained is due to the negative carbon obscuring part or all of the light. The actual distribution curve A B′ C′, Fig. 101, follows the curve of distribution of crater light throughout an angle of 20°: over

[1] This is on the assumption that the whole of the crater is of equal intrinsic brightness, which is not correct under all conditions, as has been shown by Mr. Trotter and Mrs. Ayrton. For practical electric lighting purposes this assumption can, however, be made with the reservation that with cored carbons the surface of the solid carbon is always brighter than the core. For the purpose of the present argument the discrepancies introduced by this factor may be neglected.

this range the whole of the crater is visible. Beyond 20° part of the crater is obscured, the proportion increasing until the direction 70° is reached, when the whole of the crater is hidden by the negative carbon. The light obtained in any particular direction is proportional to the apparent area of that part of the crater visible from the given direc-

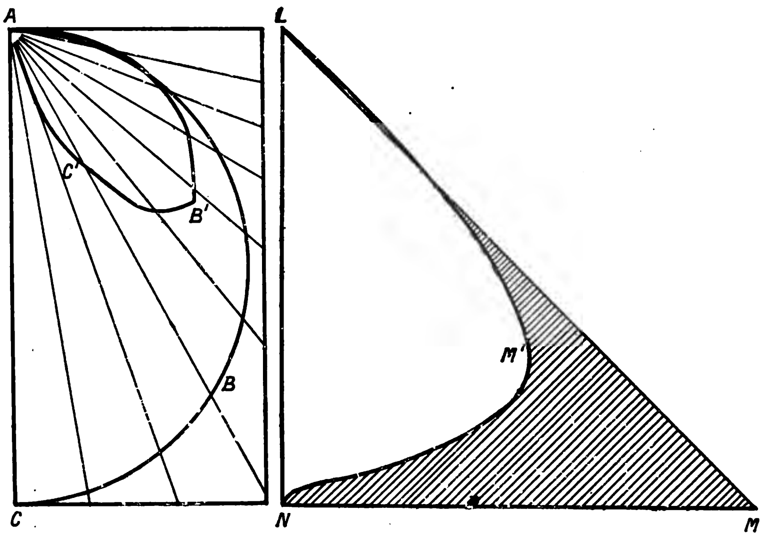


FIG. 101.—Light obscured by negative carbon in open arc.

tion. It will be seen, therefore, that the shape of the distribution curve is not due to the open arc only emitting light in the directions in which an appreciable candle-power is obtained but is caused by the light emitted in the other directions being intercepted by and absorbed in the lamp. Although the area of the curve A B C in Fig. 101 is very much greater than that of curve A B′ C′ it must not be

concluded that the loss of light is so great as would appear from these curves. The areas of these curves do not represent the amount of light radiated as has already been pointed out in Chapter IV. To find the amount of light we must draw the Rousseau figures corresponding to these two curves. These are shown in Fig. 101: the triangle L M N is the Rousseau figure corresponding to curve A B C, and the unshaded area L M′ N the Rousseau figure corresponding to curve A B′ C′. The shaded portion of L M N represents, therefore, the amount of crater light lost, amounting in this case to 36 per cent.

The degree to which the negative carbon intercepts the light from the crater having such an important effect on the amount of light obtained from the arc, it is evident that the size and shape of the negative carbon point, and its nearness to the positive carbon (length of the arc) are most important factors in determining the amount of light. Since the shape of the point of the negative carbon is itself dependent on the length of the arc, the problem of determining the best conditions of use becomes a very complicated one even when attention is confined to the interception of light by the negative carbon. There are, however, many other factors which have to be considered, such as the effect of the diameter of the positive carbon with a given current, the effect of absorption of the light from the crater as it passes through the carbon-vapour and mist forming the arc, which Mrs. Ayrton has shown is considerable, and the loss of power in the arc itself which is practically non-luminous. Further, with a cored positive carbon the effect of the diameter of the core must be taken into account, as the core is always less bright than the solid

carbon, and as this again reacts on the length of the arc it will be seen that the determination of the best possible burning conditions is an exceedingly difficult matter. Even when the best conditions for the arc itself have been found the questions of the rate of burning of the carbons and the construction of the lamp have to be considered, and it may well happen that either of these—especially the rate of burning of the carbons—may render the less efficient arc the most economical for practical purposes.

The problem is very fully discussed by Mrs. Ayrton in the eleventh chapter of her book, and the conclusions at which she arrives may be briefly summarised here. Mrs. Ayrton also takes into consideration the question of the ratio of the power consumed in the arc to the power developed by the generator. Since there is a necessary loss of power due to the arc being unstable without resistance in series the conditions of the arc should be such, if possible, that this loss is a minimum. Mrs. Ayrton shows that with constant length of arc the illuminating power and the efficiency of the arc increases with the current; with constant current the illuminating power increases with the length of arc up to a maximum corresponding to a fairly short length of arc, after which the increased absorption in the arc itself causes an actual lowering of the amount of light obtained from the arc. The ideal arc would be an infinitely short arc burning between infinitely thin carbons, and the nearest practical approach to this is to have the positive carbon so thin that the arc is, with the given current, as near to the hissing state as is practicable, the negative carbon as small as it can be for the necessary duration of burning, and the arc length such that the ratio of light emitted to

power developed in the generator is a maximum for the particular carbons.

It has already been pointed out that the higher grade carbons are more efficient than the lower grade, and, also, in spite of their greater cost and quicker rate of burning, more economical in use. Engineers who have failed to appreciate a simple advantage such as this are hardly likely to trouble themselves greatly with an attempt to obtain greater efficiency with the open arc by selecting carbons of the best diameters and burning the arcs under the best conditions. It is, moreover, most improbable even if the absolutely best result were secured from the ordinary open arc in this way, that it could compete against the flame arc.

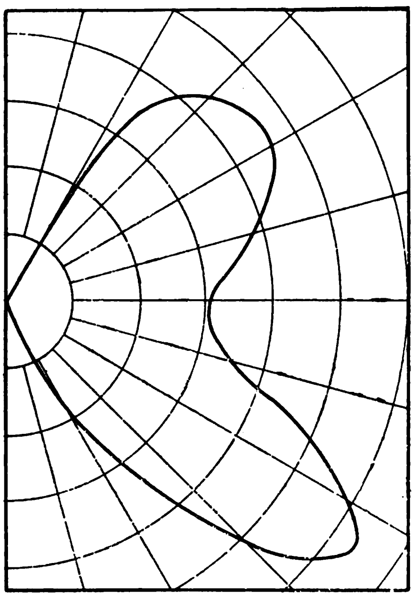


FIG. 102.—Vertical distribution curve. Open type arc: alternating-current.

Mention may here be made of the Carbone flame lamp. This lamp is not a true flame lamp but burns ordinary carbons inclined towards each other like the carbons in a flame lamp, as in Fig. 83, p. 206. By using a high voltage (90—95 volts) and a magnetic field to deflect the arc it is drawn out

into a long flame and starts properly from the tips of the carbons. The "flame" is not, however, a flame in the same sense as with chemically prepared flame carbons, but is simply a very long arc. The crater and the white tip of the negative carbon are thus fully exposed to view, and the light from them is not at all intercepted, which is distinctly an advance in the right direction. The production of a long non-luminous arc is, on the other hand, a drawback, since a large amount of power is thereby wasted. The distribution of the light with this lamp is similar to that with the ordinary flame lamp (see Fig. 104). Figures for its efficiency will be given later.

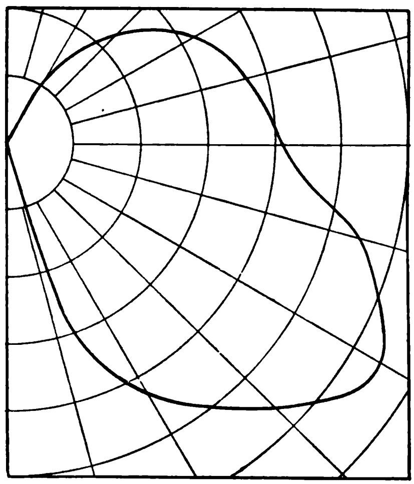


FIG. 103. — Vertical distribution curve. Enclosed arc: direct-current: opal globe.

The distribution of the light from an alternating-current open arc is shown in Fig. 102. Since two craters are formed the curve is approximately the same above and below the horizontal. On account of the amount of light radiated above the horizontal this arc is not so suitable for general use as a direct-current arc.

The distribution curves for enclosed arcs are very irregular on account of the flat ends of the carbons. As the crater and white spot only occupy a small portion of

the carbon ends, the amount of light received in a given direction depends at a particular moment on the position of the arc at this moment. The use of diffusing globes with these arcs is, therefore, always desirable. A typical curve for an arc with opal globe is shown in Fig. 103. The efficiency of the enclosed arc is considerably lower than that of the open arc, but the long burning hours of the carbons and the consequent saving of labour in trimming may more than counterbalance this disadvantage where labour is dear or the lamps are spread over a wide area.

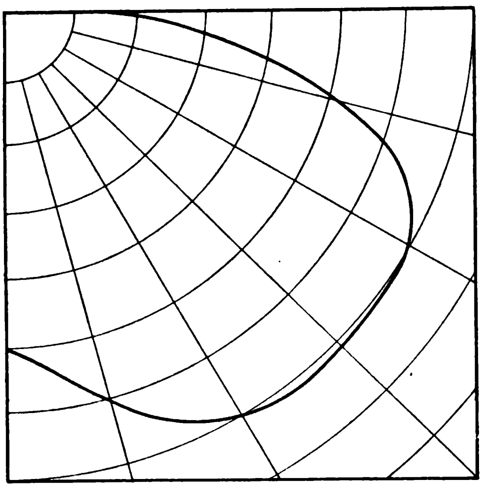


FIG. 104.—Vertical distribution curve. Flame arc: direct-current: inclined carbons.

The distribution of light with flame lamps having inclined carbons is shown in Fig. 104. The concentration of the light in the angles near to the vertical is distinctly a disadvantage, but the very much higher efficiency of the flame arc more than makes up for this.

Although the flame lamp has now been in commercial use for three or four years, it is hardly to be supposed that anything like finality has been reached. This is fairly evident if the lamps now on the market are examined.

Though all these lamps follow fairly closely the original pattern, considerable differences will be found in the shape of the economisers and in the carbons used. Flame arc carbons now on the market may be classed as "positives" or "negatives" according as the core canal is large or small. Thus an 8 *m/m* carbon with a large core canal (about 4 *m/m*) is a positive, and with a small core canal (about 2·5 *m/m*) is a negative. It will be found that in certain cases the negative carbon is not cored with flame producing material, and there are, therefore, three types of carbon to consider :—

(1) Positive carbons flame-cored.

(2) Negative carbons flame-cored.

(3) Negative carbons ordinary-cored.

and as a fourth carbon sometimes used in flame lamps we have

(4) Ordinary solid carbons.

Flame lamps for alternating-current are always constructed (to the writer's best knowledge) to burn with two flame-cored negatives of the same diameter, but in direct-current lamps various combinations are used. Generally the positive carbon is 1 *m/m* larger in diameter than the negative (*e.g.*, 9 *m/m* and 8 *m/m* or 8 *m/m* and 7 *m/m* are paired), but the types of carbons paired vary greatly. Thus a flame-cored positive may be combined with a flame-cored negative, or a flame-cored positive with an ordinary-cored negative; or two flame-cored negatives may be combined; or a flame-cored positive with an ordinary solid negative. Almost any combination is possible, but those enumerated above are the ones most generally met, the most usual being the second and the third. The choice depends almost

entirely on the shape of the economiser and the position relative to it at which the arc burns. If the lamp is so constructed that this position can be adjusted then it will generally be possible to adjust it to suit any desired combination of carbons. But when adjusted to suit one combination the lamp will not burn satisfactorily with another combination as the rates of burning of the carbons will be different. Thus if a flame-cored positive and an ordinary-cored negative burn well it is most probable that two flame-cored negatives will burn at unequal rates, producing an unsteady arc as already explained on p. 243. It is most important, therefore, that the correct carbons should be used to trim the lamps. All makers now adopt the custom of painting the butt end of the carbons when they are flame-cored, and it is easy to see at a glance from the size of the core canal whether the carbon is a "positive" or "negative."

For the same reason it will be found that lamps must be specially adjusted if white or other coloured flame carbons are used, since the arcs with these colours are not quite as long as the yellow flame arcs, and the position of the arc relative to the economiser is consequently altered. Attention must also be paid to whether the carbons are metal-cored, coppered or plain, as this materially affects the burning in the same manner.

By far the most efficient light is given by yellow flame carbons. For direct-current arcs the combination of a flame-cored positive and an ordinary-cored negative gives more light than the combination of two flame-cored negatives. The substitution of a flame-cored negative for an ordinary-cored to burn with a flame-cored positive slightly

increases the efficiency, but the presence of flame core in the negative appears to be undesirable for other reasons and to have but very slight effect on the amount of light.

There have recently been introduced into this country two types of flame lamps which depart considerably from the normal design. The one of these is the Crompton-Blondel lamp, the design of which is based on the researches of Prof. Blondel. This lamp has the carbons arranged vertically, the upper carbon being an ordinary carbon about 9 *m/m* in diameter, and the lower a specially manufactured flame carbon about 14 *m/m* in diameter. The flame carbon is similar in many respects to the original Bremer carbons, the flame producing material being incorporated in the carbon before it is baked instead of being introduced into the core. The carbon consists essentially of two parts, a central portion forming the bulk of the carbon and containing the flame producing material, and an outer ring or shell about 1—2 *m/m* thick of ordinary carbon. It is claimed that a much higher percentage of flame producing material can be introduced in this way, without leading to unsteadiness in the arc, a much more efficient arc resulting in consequence. An additional advantage lies in the, comparatively, much slower rates of burning of the carbons involving less frequent trimming of the lamps. The distribution of the light owing to the use of a vertical arc is also better for practical purposes. The figures given for the efficiency of these arcs are remarkably good, but at present await confirmation: these are given later.

The second lamp is the so-called regenerative flame lamp recently introduced by the Jandus Company.[1] The feature

[1] See *Electrical Engineering*, Vol. III., p. 299, February 27, 1908.

of this lamp is that the arc burns in an enclosure (as with enclosed lamps), special arrangements being provided to lead away the fumes and prevent them condensing on the enclosing globe. Carbons arranged vertically and of special construction are employed, and the features characteristic of the Blondel lamp, distribution of light and long burning hours, are also claimed for this lamp. The lamp has only just been placed on the market, and full particulars of its performance are not yet available.

One of the main difficulties which both these lamps seek to overcome is the rapid rate at which the carbons used in ordinary flame lamps are consumed. As has been pointed out already, this has necessitated using very long carbons in order to obtain at all reasonable burning hours, and the use of these long carbons has further involved the employment of coppering or metal cores to increase the conductivity, resulting in considerably increasing the price of the carbons. Attempts have been made to overcome this difficulty by using magazine lamps holding a number of short carbons (12 inches—16 inches). This principle is an old one, having been frequently applied to open and enclosed lamps. There are now several types of magazine flame lamps on the market, in some of which (*e.g.*, the Oliver Oriflamme lamp and the General Electric Co.'s Angold magazine lamp) the carbons are brought into use successively, a fresh pair being substituted as soon as one pair is consumed, whilst in others (*e.g.*, the Gilbert flame lamp) a number of carbons are arranged side by side and burn alternately, the arc forming always between the longest pair for the time being.

In Table XXIX. are summarised the principal data for the various types of arc lamps. On account of the

difficulties attending arc lamp photometry the figures must be taken as to a certain degree approximate, and it must be

TABLE XXIX.

Type of lamp and conditions of circuit.	Current in amperes.	Arc P.D. in volts.	Watts.		M. S. C. P.	Watts/M. S. C. P.	
			Arc.	Total per lamp.[1]		Arc.	Total.[1]
Open arc. Direct-current, 2 lamps on 100 volts .	10	43	430	500	350	1·23	1·43
Open arc. Direct-current, 5 lamps on 230 volts .	10	43	430	460	350	1·23	1·32
Open arc. Direct-current, 5 lamps on 230 volts, "soot" carbons . .	10	43	430	460	420	1·02	1·09
Open arc. Alternating-current, 3 lamps on 105 volts	10	33	330	350	250	1·32	1·40
Enclosed arc. Direct-current, 1 lamp on 100 volts	5	80	400	500	220	1·82	2·27
Enclosed arc. Alternating-current, 1 lamp on 105 volts	7·5	80	600	790	320	1·88	2·47
Carbone lamp. Direct-current, 1 lamp on 100 volts	10	90	900	1,000	1,000	0·90	1·00
Flame lamp. Direct-current, 2 lamps on 100 volts, yellow light . . .	10	45	450	500	1,200	0·38	0·42
Flame lamp. Direct-current, 2 lamps on 100 volts, white light . . .	10	45	450	500	750	0·60	0·67
Flame lamp. Alternating-current, 2 lamps on 100 volts, yellow light . .	10	45	450	500	1,200	0·38	0·42
Blondel flame lamp. Direct-current, 2 lamps on 100 volts[2]	10	43	430	500	2,400	0·18	0·21

particularly remembered that an arc is not like an incandescent lamp, which is delivered in a complete condition to

[1] The values of watts per candle (total) include the losses in series resistance and represent therefore the true working results.

[2] Values obtained from data published by Prof. Blondel.

the user. The light actually obtained from arc lamps in practical use depends very largely on the care taken to keep the lamp always in perfect working order, and on the steadiness of the circuit on which they are used. If an incandescent lamp is temporarily over- or under-run it will work at an unusual efficiency during that period, but on the conditions returning to normal it will have again its normal candle-power and efficiency. But if the voltage on an arc lamp is continually varying the carbons are never able to burn to their normal shapes, and will not at any time give normal results either as to rate of burning, amount of deposit, amount of light or efficiency.

Table XXIX. brings out very clearly the great advance brought about by the development of the flame lamp. Some further aspects of this question will be discussed in the last chapter: it is sufficient to remark here that the flame lamp gives promise of bringing about as great an alteration in arc lighting as the metallic-filament lamps are effecting in incandescent lighting.

It is naturally impossible to draw up a table showing the candle-power, etc., for all the different arcs met with in practice: as a rough but serviceable approximation the figures for watts per candle in Table XXIX. may be used to estimate the candle-power of any given lamp, since it is only necessary to divide the watts consumed in the lamp by these figures to obtain a value for the mean spherical candle-power.

From the data in Table XXIX. the figures in Table XXX. have been worked out showing the cost of lighting per 1,000 candle-hours with arc lamps. The costs include the cost of energy and carbons, the latter being taken at current prices, but make no allowance for depreciation of lamps and

cost of attendance and trimming since these items vary immensely according to circumstances. The depreciation depends naturally on whether the lamps are used indoors or outdoors, and the cost of this item per 1,000 candle-hours depends entirely on how many hours a year the lamps are run. The actual cost of trimming depends on the local conditions, the distance the lamps are apart, etc., and the cost per 1,000 candle-hours again on the hours run during the year. It is better, therefore, to neglect these items in the table and make allowances for them in each special case.

TABLE XXX.

COST PER 1,000 CANDLE-HOURS WITH ARC LAMPS.

	W./M. S. C. P. Assumed.	Cost per B.O.T. Unit.							
		1*d.*	2*d.*	3*d.*	4*d.*	5*d.*	6*d.*	7*d.*	8*d.*
Open type arcs. "Retort" carbons	1·4	1·6	3·0	4·4	5·8	7·2	8·6	10·0	11·4
Open type arcs. "Soot" carbons .	1·1	1·4	2·5	3·6	4·7	5·8	6·9	8·0	9·1
Enclosed arcs .	2·3	2·6	4·9	7·2	9·5	11·8	14·1	16·4	18·7
Flame arcs. Yellow	0·4	0·6	1·0	1·4	1·8	2·2	2·6	3·0	3·4
" White	0·7	0·9	1·6	2·3	3·0	3·7	4·4	5·1	5·8
Carbone arc . .	1·0	1·2	2·2	3·2	4·2	5·2	6·2	7·2	8·2
Blondel arc . .	0·2	0·5	0·7	0·9	1·1	1·3	1·5	1·7	1·9

CHAPTER XI

MISCELLANEOUS LAMPS

The Magnetite Arc.

Simultaneously with the development of the flame arc which has already been described, there has been going on in America the development of another type of arc which has become generally known as the magnetite arc, though this name as applied to the latest form is somewhat of a misnomer. It is remarkable that the experimental work in connection with this arc has been practically confined to America, and that up to the present magnetite arc lamps are only commercially in use to any noteworthy extent in that country. Reasons connected with the economical objection in America to any lamp involving frequent trimming, which have been sufficiently powerful in the past to lead to the almost universal adoption in that country of the enclosed arc to the exclusion of its more efficient competitor the open arc, and which operated, and still operate, strongly against the introduction of the ordinary flame arc, have probably a good deal to do with this, since there has been every encouragement to experiment in the production of an arc lamp of high efficiency and using slow burning electrodes such as the magnetite arc.

In the magnetite arc the use of carbon as an electrode has been abandoned, and with it the idea of obtaining much light from the incandescent electrode surfaces. Instead

material is used for the electrodes which, when volatilised into the arc, gives an intensely luminous flame. There is some reason to think, and this view is held by Prof. Steinmetz, to whom the development of the magnetite arc is due, that the electrode material is not simply volatilised into the arc and that it does not cause the arc flame to become luminous in precisely the same way as do the chemicals vapourised into the ordinary flame arc. This question will be referred to in the next chapter: it is sufficient here to note that some colour is lent to this view by the fact that in the magnetite arc all the flame producing materials are contained in the negative electrode, usually the cooler electrode in an arc, whereas in the ordinary flame arc it is common, though not universal practice, to have the flame producing materials in the positive electrode only.

The materials used in the magnetite arc to produce a luminous flame are magnetic oxide of iron and titanium oxide. Both iron and titanium oxides give a highly luminous arc, but it seems that the more efficient is titanium oxide. Since, however, titanium oxide is a non-conductor when cold, the presence of the magnetic oxide of iron is necessary to give conductivity to the electrode. It appears, therefore, that the iron oxide now plays rather a secondary part in the magnetite arc. In addition to these oxides the electrode contains chromium oxide. This oxide is not used for the purpose of increasing the luminosity of the arc, but in order to retard the evaporation of the two other constituents; being less easily fusible than these, it is claimed that it does not melt, but remaining solid, holds the molten oxides as a sponge holds water. The evaporation of

the iron and titanium is consequently both slower and more regular. It may be pointed out that the carbon powder in the core of a flame carbon undoubtedly plays the same *rôle* towards the calcium fluoride, and in all probability also towards the potassium silicate in an ordinary cored carbon.

These finely powdered oxides are mixed in the correct proportions and are made up into rods by being pressed into thin-walled iron tubes. In the earlier lamps the negative electrode made in this way was used as the lower electrode, and a block of copper was used as the positive upper electrode. This had the disadvantage of practically sacrificing what light was given by the incandescent tip of the negative electrode, and in the latest lamps the position of the electrodes is reversed. It was found on reversing the electrodes that copper was no longer suitable as a positive, as the copper oxide which was formed during the burning of the arc covered the surface of the anode with an insulating layer which prevented the arc re-striking. To overcome this difficulty a composite electrode was used which, when oxidised, gave a conducting slag; this slag formed always the true electrode surface and was slowly evaporated by the arc, and reproduced from the under metallic surface. This electrode was at the same time given a roughened surface and was made smaller so as to work at a higher temperature, both these changes helping to keep the slag always adherent to the metal. A further disadvantage of reversing the electrodes was the production of a mantle of redeposited oxides on the negative electrode, which accumulated and in time hung down over the arc, considerably obscuring its light; this difficulty has been overcome by the provision of very efficient ventilation around the negative electrode

which effectually removes the oxides without allowing them to deposit on the electrode.

The magnetite arc is a long arc and operates at a high voltage. The length of the arc is about an inch. The lamps at present made operate at a voltage of 60—65 across the arc and at a current of 4 amperes. The lamps are only suited for direct-current or rectified alternating-current. It is stated that a twelve inch negative electrode has a life of approximately 150 hours, so that a lamp will burn for this time with one trim. The long life of the electrode is a natural consequence of the fact that it is composed of oxides which therefore do not burn as does the carbon of the ordinary arc lamp electrode.

Published results of tests on the consumption of these arcs are few; it would appear from a paper by Little[1] that it is in the neighbourhood of 0·6 to 0·8 watts per candle (mean spherical), which is about double the power consumption per candle of a 10 ampere flame arc. The efficiency of a magnetite arc at 10 amperes appears from the same paper to be considerably better, but since only low current lamps have been produced there are evidently difficulties in the way of the satisfactory operation of higher current arcs. To counter-balance this low efficiency (according to the latest ideas) the fact that the magnetite arc is a small light unit must be taken into consideration, since this is from very many points of view a great advantage. From the figures given we may take the mean spherical candle-power of the magnetite arc as being in the neighbourhood of 250—300. The lamp is therefore more comparable with enclosed lamps than with flame lamps, and compared with these it

[1] *The Electrician*, May 12, 1905, Vol. LV., p. 120.

possesses the advantages of approximately 50 per cent. longer burning hours and three times the efficiency.

The Mercury-Vapour Lamp.

The earliest experiments to obtain an electric lamp which utilised the arc burning between mercury electrodes in an evacuated tube as a source of light date back to about 1860, but no lamp which could be described as at all practical was obtained until in 1892 Arons succeeded in designing a mercury-vapour lamp of the form shown in Fig. 105. In this lamp the arc burns between the two mercury surfaces M and M′, and fills whilst burning the whole of the U shaped tube. The Arons lamp, though it contains all the essential elements of a successful mercury-vapour lamp, remained for many years only a laboratory or scientific appliance. In 1900—1901 Mr. P. Cooper-Hewitt (in America) as the result of a careful study of the laws governing the burning of the mercury arc succeeded in designing a really commercial form of lamp. A little later Mr. C. O. Bastian (in this country) developed a similar lamp. Since this period the possibilities of the mercury-vapour lamp have been much studied, and various attempts, more or less successful, have been made to overcome its chief defect, the unpleasant colour of the light which it gives.

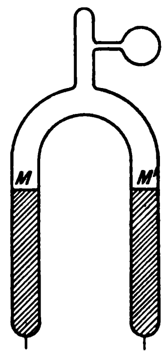


Fig. 105. — Arons mercury - vapour lamp.

The mercury-vapour arc is a true arc, and must not be confused with a vacuum discharge. The conducting vapour path is not the residual gas left in the tube after exhaustion

but is mercury vapour produced from one or both of the electrodes. Whether this vapour is produced simply by distillation of mercury from the electrode surface as the result of the intense local heating at the point from which the arc starts, or whether it is partly the result of the electrical projection of mercury particles into the vapour stream must be regarded as to a certain extent an open question. It is, however, fairly well established that a large part, if not the whole, of the vapour is produced by distillation alone. Various attempts have been made to determine if possible whether the amount of mercury carried over from one electrode to the other bears any relation to the amount which would be separated according to Faraday's law of electrolysis, and it has been established as the result of these experiments that no such relation exists.

Mercury-vapour lamps as at present constructed consist essentially of a glass tube, the length and diameter of which is proportioned to the voltage and current at which it is desired to work the lamp, having electrodes sealed into the glass at each end, exhausted of air and partially filled with mercury. The tube may be straight, as in the Cooper-Hewitt lamp, or it may be bent into U form as in the larger Bastian lamps, or into a zigzag as in the smaller Bastian lamps. The object of bending the tube is simply to enable it to be fitted into a smaller space in the lamp. In the Cooper-Hewitt lamp one end of the tube, that into which the anode is sealed, is generally of larger diameter (see Fig. 108), so as to form a cooling chamber in which the volatilised mercury can recondense. Both electrodes can be of mercury (connected with the outside by platinum leads sealed in the glass), and this is the case in the Bastian lamps, but it is

sufficient for the production of the arc if the cathode alone is mercury, and in the Cooper-Hewitt lamps an iron or carbon anode is used.

The resistance of the arc depends primarily on the pressure of the mercury vapour in the tube. When the current is increased more mercury vapour is produced from the cathode and the resistance falls proportionately. Hence the characteristic of the mercury-vapour arc is similar to that of the ordinary arc; the voltage falls rapidly at first with increase of current and then becomes almost stationary, but showing a slight tendency to fall. It appears, however, that if the current is increased beyond a certain limit the voltage rises again rapidly, and the voltage necessary to maintain the arc may become in consequence so great that the voltage of the supply is no longer sufficient and the arc goes out. This phenomenon is due to the fact that the arc is enclosed in a sealed tube, and it is not possible in consequence for it to work at a constant (or nearly constant) temperature as does the ordinary arc. Directly the rate at which the mercury vapour is produced exceeds a certain amount, recondensation no longer takes place sufficiently rapidly to keep the temperature low, and there is a large increase of resistance and consequent rise in voltage. The upper limit of current (before the voltage rises) depends therefore on the efficiency of the cooling. This is well shown by the curves in Fig. 106 from a paper by Dr. Recklinghausen,[1] in which curve A shows the characteristic of a lamp at room temperature, and curve B the characteristic of the same lamp exposed to cold winds in the open air. It is

[1] *The Electrician*, Vol. XLIX., p. 393, June 27th, 1902.

sometimes found that lamps (for example, of the Bastian type) in which inadequate cooling arrangements exist go out without any apparent reason and then a little later relight: this is doubtless due to the tube getting overheated, the relighting occurring when the tube has again cooled down sufficiently. From the shape of the characteristic it is obvious that mercury-vapour lamps like all other arcs must

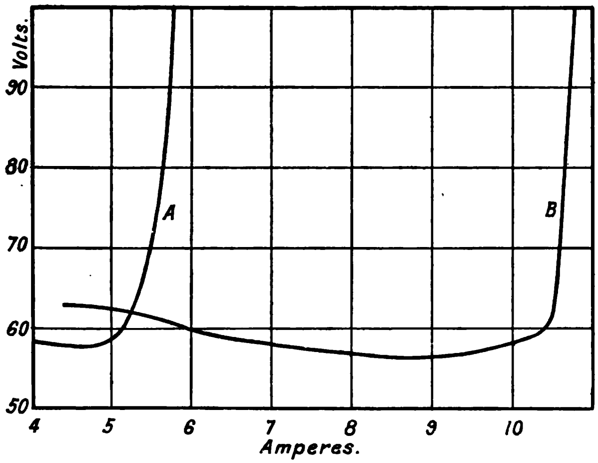


FIG. 106.—P.D.-current curves. Mercury-vapour lamp. *A*, at room temperature. *B*, in the open. (*Dr. Rechlinghausen*).

be run in series with a steadying resistance, and this in order to give the best results should have such a value that the current which flows is that corresponding to the last point on the characteristic before the rise in voltage.

With a given tube the relations between voltage and current must be studied by means of the characteristic curves already referred to. It is stated that when the

length of tube is altered the voltage is proportional to the length; this can be only approximately true as there is a certain drop of potential at the electrodes, about 13 volts, which will be independent of the length of the tube. Mr. Cooper-Hewitt also found that the voltage with a given current is inversely as the diameter of the tube. Since the cross section of the arc varies as the square of the diameter it follows that the other changes introduced by increasing the diameter (alteration of the volume and hence of the vapour pressure, and alteration of the cooling surface) produce a change in the specific resistance of the arc which is directly proportional to the diameter of the tube. For if ρ be the specific resistance of a tube of diameter d and length l we have

$$V = A\,k\,\frac{\rho\,l}{d^2}$$

when ρ is constant. Since in the mercury-vapour lamp

$$V = A\,k'\,\frac{\rho'\,l}{d}$$

when ρ' is the specific resistance under the given conditions it follows that

$$\rho' = c\,d\,\rho$$

where c is a constant.

The mercury-vapour lamp presents the same difficulty as all other arcs that in order to start it the electrodes must be brought into contact, or else a current must be started in some other way, as for example by a high-voltage discharge. The simplest way out of this difficulty is to arrange the tube so that it can be tilted into such a position that the mercury forms a complete bridge from one electrode to the other; on then releasing the tube as the mercury runs back to the cathode it strikes and draws out the arc.

The tilting may be effected by a cord attached to the lamp, but this involves two processes for lighting the lamp, switching on and tilting the tube, the latter being not a very convenient operation to perform in the dark. To get over this difficulty the tube can be tilted automatically by a magnet fixed to the lamp case acting on an armature attached to the tube. This may be connected of course in various ways to suit the particular circumstances. Various other ingenious methods have been tried for starting the arc. One of these is shown in Fig. 107. The tube is arranged with an auxiliary mercury anode at A. On open circuit the mercury bridges from A to the cathode B. On switching on, current flows from P through the contact C, around the solenoid S and through the mercury to N, the negative pole. The solenoid S being thus energised lifts a float F in the mercury at A, thus causing the level of the mercury to sink and starting an arc between A and B. This arc renders the whole tube conducting, and an arc immediately starts between D and B. The current to this arc is led round a cut-out solenoid at E, and this opens the circuit of the starting arc at C and puts this arc out; the cut-out need not put this arc out as the auxiliary arc can continue burning without disadvantage (it is

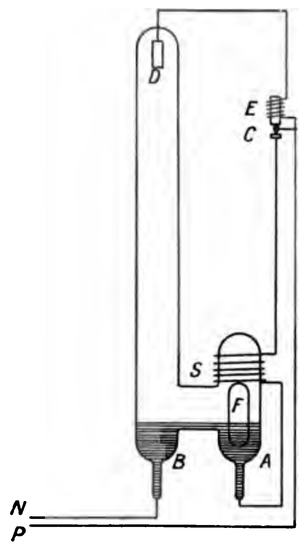


FIG. 107.—Method of starting mercury-vapour lamp.

claimed even that it steadies the main arc); in this case the cut-out on lifting the contact at C merely puts extra resistance into this circuit.

By another suggested method a carbon filament is suspended from the anode and dips normally into the mercury cathode; when the lamp is switched on the level of the mercury is caused to sink by means of the action of a solenoid on a float in the mercury, and an arc is struck

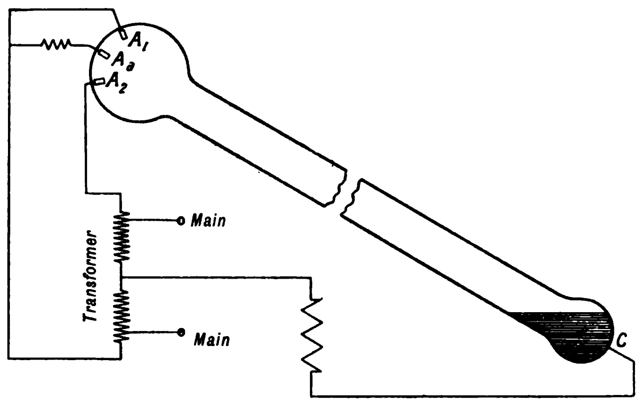


FIG. 108.—Mercury-vapour lamp for single phase alternating current.

between the filament and mercury which immediately lengthens out to fill the whole tube. These methods, though ingenious, are to the writer's belief not at present adopted commercially. The method of starting the arc by a preliminary high-voltage discharge has also hitherto not been commercially used, but a new lamp designed on this principle has just been brought out by Mr. Cooper-Hewitt.[1]

[1] See *The Electrical World and Engineer*, Vol. LI., p. 782, April 11th, 1908.

The ordinary mercury-vapour lamp cannot be operated on alternating-current because as soon as the value of the current sinks to zero the arc goes out, and cannot restart except by restriking.[1] For alternating-current, therefore, the lamps must be so arranged that the current at the mercury cathode never falls to zero. This is easily effected with three phase current by connecting the cathode to the neutral point and the terminals of each phase to three separate anodes. Under these circumstances the current flowing to the mercury is never zero and is always in the same direction. With single phase supply the lamp is constructed with two primary and one auxiliary anode, A_1, A_2 and A_a, Fig. 108. The primary voltage is applied to a transformer which is so connected, as shown in the figure, that A_1 and A_2 are always positive (alternately) to the cathode C, and by suitable proportioning of the reactances the two half waves are caused to overlap so that the current to C never falls to zero. The auxiliary electrode A_a serves to start the lamp.

The chief objection to the mercury-vapour lamp is the colour of the light which it gives; the chief advantage is the

[1] This property of the mercury-vapour arc has led to the invention and development of mercury-vapour rectifiers for converting alternating into direct-current. Since these rectifiers are not lamps in the sense in which this book deals with lamps they will not be described here. It may be remarked, however, that their development on a practical scale has been remarkable in America: in one installation six rectifiers are used for rectifying current for an installation of 324 magnetite lamps. This is particularly interesting, as one type of lamp is here used merely as an auxiliary for the production of light by a lamp of another type. It seems possible, and even probable, that the use of the mercury-vapour arc as a rectifier will be of greater importance in the future than its use as a source of light.

comparatively large light source of low intrinsic brilliancy. The colour of the light is a most unpleasant green, and the almost complete absence of red and yellow lines in the spectrum causes all coloured objects illuminated by mercury-vapour lamps to lose their natural colours, and people present the appearance of the dead. It is claimed that where colour is of no importance, as for example in drawing offices, accurate work can be performed with mercury-vapour illumination more easily and with less fatigue than with other illuminants. It is difficult to believe that this is really the case except in so far as the secondary effects due to intense illuminants (uneven distribution, etc.) are eliminated, but these can of course be eliminated in other ways with lamps giving light of a more suitable colour. It is also claimed that for lighting large spaces the mercury-vapour lamps may be advantageously used in conjunction with other illuminants to balance their colour defects, as for example with yellow flame arcs, and this contention seems reasonable. Resort cannot be had to the use of coloured glass to filter out the excess of green and blue rays, since the red rays which are required are actually absent, and of course are not produced by this device. Attempts have been made to improve the colour of light by using fluorescent reflectors, such as rhodamin, behind the lamps, but these produce but little effect even when new, and very quickly lose their fluorescing power.

The extreme colour difference and the large size of the light source makes the photometry of mercury-vapour lamps a difficult matter, and the data available for efficiency are consequently meagre. To overcome these difficulties photometry has been often effected by measuring the illumination

produced in a given room when lighted by various illuminants (see p. 52), but this method is most unreliable unless a great number of precautions are taken. Tests by Clifford[1] on a 104 volt 3·5 amp. Cooper-Hewitt lamp gave the following results :—

TABLE XXXI.

	Without reflector.	With reflector.
Average watts . . .	364	364
M.H.S.C.P. . . .	575	1,200
W./M.H.S.C.P. . . .	0·63	0·303

The best efficiency, as has been pointed out, is with the maximum current before the voltage rise, and the power consumption appears from data available to be in the neighbourhood of 0·6 watts per candle (mean spherical). This figure shows that the mercury-vapour lamp, though at the time of its introduction it promised to be one of our most efficient light sources, can no longer compete on this ground alone against the later developments in flame arcs. On the other hand, the maintenance cost is very low, as nothing has to be supplied to the lamp except power. The life of the tubes is stated to be from 1,500 to 7,000 hours; a slight blackening of the glass occurs, but the diminution in efficiency on this account is very slight. The intrinsic brilliancy is of the order 0·4 to 0·6 candles per sq. cm.

Attempts have been made to improve the colour of the light by introducing other metallic vapours into the tube, and various amalgams have been tried for this purpose. None

[1] National Electric Light Association, June, 1906.

of these attempts have been successful as yet, the difficulties encountered being discolouration of the glass tube and uncertainty of the light, in that sometimes only a pure mercury arc burns in spite of the presence of the other metals. The problem has been attacked in another direction by Dr. Kuch, of the firm of Heraeus, of Hanau.[1] This firm having developed the manufacture of apparatus from fused quartz undertook experiments on the construction of mercury-vapour lamps from quartz instead of glass tubes, with the result that it was found possible to push the current-density and hence the internal temperature and pressure to much higher values. Under these conditions it is claimed very great improvements are effected. Working with an internal pressure just under one atmosphere (higher pressures being regarded as unsafe for practical purposes), the specific resistance of the vapour path is so greatly increased that instead of tubes about 100 centimetres long and 3·4 centimetres diameter for 110 volts, tubes only 8 centimetres long and 1 to 1·5 centimetres diameter are required. This makes the lamp much more convenient and enables it to be mounted in a globe and case similar in size and shape to an ordinary arc lamp. The greatest gains are, however, in the efficiency and colour of the light. The published figures claim a consumption of 0·27 watts per candle (mean spherical), which is only half that of the glass lamp, and it is stated that in addition to the line spectrum of mercury there is fairly strong continuous spectrum, so that

[1] See a paper by Dr. Bussmann before the Elektrotechnisher Verein. *Elektrotechnishe Zeitschrift*, Vol. XXVIII., p. 932, September 19th, 1907. See also a condensed report in *Electrical Engineering*, Vol. II., p. 549, October 10th, 1907.

the colour of the light is far more nearly normal. This spectrum is due purely to the heating effect, and it is stated that attempts to measure the internal temperature of the arc by means of a thermocouple indicate a temperature of 6000° C. at the normal working voltage. This figure appears very questionable, but it is of interest to note that the gain in efficiency has apparently been obtained by reverting to the old method of obtaining light by incandescence. In its other details the lamp is similar to the lamps already described and does not call for special remark. The life of the tubes is guaranteed at 1,000 hours, but it is believed that much longer life will be attained in practice.

The Moore Vapour Lamp.

The idea of utilising the light given by an electrical discharge in a tube containing rarefied gas—the Geissler tube—as a practical illuminant probably dates back to the discovery of these discharges, but the practical difficulties have been great, and it is only comparatively recently that the problem has been seriously attacked. To Mr. McFarlane Moore belongs the distinction of having successfully overcome these difficulties and of producing a practical commercial lamp.

The Moore light, as it is named, is simply a high-voltage vacuum discharge through a partially exhausted glass tube. The tube is made of great length and fixed permanently in position by being passed through brass rings hung from the ceiling of the room or hall it is desired to illuminate. The total length of tube may amount to 200 feet; naturally such a length cannot be transported, so that the lamp has to be made up by jointing suitable lengths of tubing together and

evacuating *in situ.* In general the tubes are so built up as to follow the contour of the ceiling. The two ends of the tube are led into an iron box containing the transformer for stepping up the supply voltage to the necessary value, which may be as much as 10,000 to 12,000 volts. The electrodes are graphite connected to platinum leading-in wires. All the high-voltage terminals are completely enclosed, so that all danger from this source is avoided. The diameter of the tubes now used is $1\frac{3}{4}$ inches. The greatest difficulty found with this system of lighting is that the vacuum diminishes during life owing to absorption of the gases by the tube walls, and the essential feature of the Moore tube is the provision of an ingenious valve for admitting fresh gas and maintaining a constant vacuum. This valve, which is contained in a branch from the main tube, is shown diagrammatically in Fig. 109. The bottom of the tube B is sealed with a carbon plug F, and the top A is left open: the tube C connects to the main lamp tube. The carbon plug, F, is normally completely covered with mercury into which dips a glass plunger P connected to an armature of soft iron wire, I. This armature is surrounded by a solenoid S connected in series with the primary of the transformer. When the vacuum decreases owing to the absorption of gas the conductivity of the gas

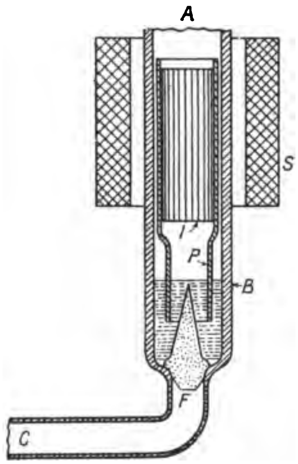


FIG. 109.—Valve of Moore vapour lamp.

increases, and hence both the secondary and primary transformer currents increase. The increase of the current through the solenoid S raises the armature I and the plunger P: the level of the mercury consequently falls and the tip of the carbon plug is exposed, whereupon a little air filters through into the tube. The original resistance is restored and the armature again falls, closing the plug. This feeding takes place normally about once every minute: the vacuum is approximately 0·1 *m/m* of mercury, and the valve keeps this constant within 10 per cent. The connections of the transformer and tube, etc., are shown diagrammatically in Fig. 110. The actual current flowing in the tube is about 0·3 amperes.

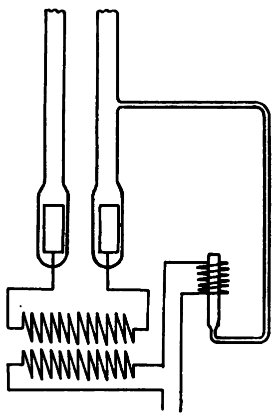


FIG. 110.—Diagram of connections of Moore vapour lamp.

The colour and the efficiency of the light depend on the gas in the tube. The best results are obtained with nitrogen, which gives, however, a somewhat pink light; atmospheric air is not so efficient as nitrogen, and carbon dioxide only about half as efficient, but gives a perfectly white light. When nitrogen is used the air is aspirated over phosphorus before it comes to the feeding valve, and when carbon dioxide is used the leading-in tube is connected to an ordinary Kipps apparatus, in which the gas is generated by the action of hydrochloric acid on marble.

The curves in Fig. 111[1] show the variation in current and

[1] *Electrical World and Engineer*, Vol. XLIX., p. 865, May 4th, 1907.

efficiency at different gas pressures. It will be seen that the pressure chosen of 0·1 m/m is the most efficient, and since the current characteristic is rising at this pressure, allows effective operation of the regulating valve.

The measurements of candle-power and efficiency of these tubes present the same difficulties on account of the size of

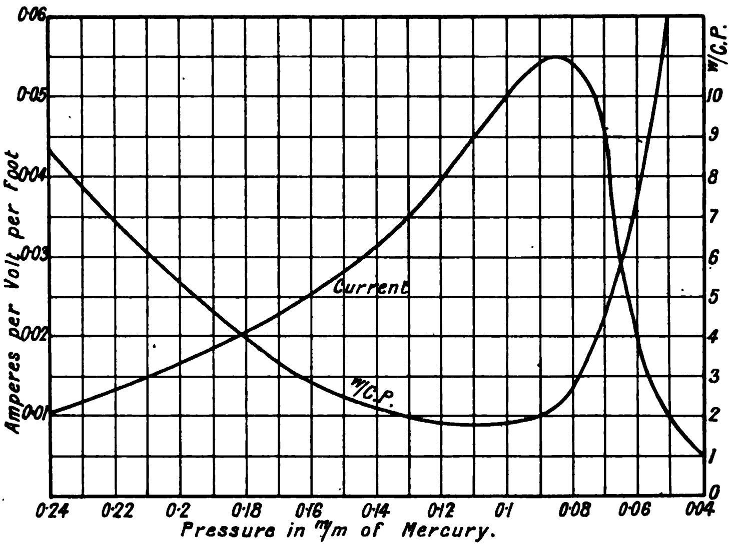


FIG. 111.—Current and watts per candle, and vapour pressure. Moore lamp. (*McFarlane Moore.*)

the light source as do those with mercury-vapour lamps. The curve in Fig. 112, from data given by Mr. Moore, shows a power consumption of 1·6 watts per candle, which is very little affected by variations in the supply voltage. Measurements made by Prof. Fleming on the Savoy Hotel installation gave results varying from 1·75 to 1·95 watts per candle.

The tube itself must be operated by alternating-current,

but a direct-current supply can be used through the intermediary of a small rotary transformer. Any periodicity above 25 is suitable.

The Moore tube has been only quite recently perfected, and the installation at the Savoy Hotel, consisting of a tube 176 feet long, is the only one which has been put up in this country. A photograph of this installation is given in the frontispiece. A certain number of installations have been put up in America. Those who have seen the Savoy installation will probably agree that the Moore tube

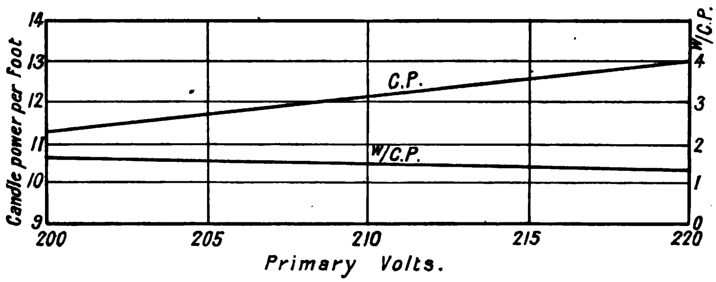


FIG. 112.—Characteristic curves. Moore vapour lamp. (*McFarlane Moore.*)

represents the most beautiful form of electric lighting yet developed, producing as it does a steady, evenly distributed illumination with a source of low intrinsic brilliancy.

CONCLUSION.

It is very difficult to make an estimate of the true cost of lighting with any of the lamps described in this chapter, as they have been so recently introduced that particulars of any value of the life of the lamps are not available. The peculiarities of the vapour lamps in the way of light

distribution, moreover, render comparison on the usual lines somewhat unfair. It is better when comparing lamps of this type with the more usual electric lamps to base the comparison of cost on the actual illumination produced, since it may well happen that in spite of a lower working efficiency of the lamp itself, the desired illumination can be produced more cheaply owing to the even distribution avoiding any useless concentration of light at certain points. Nevertheless, figures are given in Table XXXII. showing the cost per 1,000 candle-hours in pence, the only cost taken into account being that of the energy used.

TABLE XXXII.

ENERGY COST PER 1,000 CANDLE-HOURS: MISCELLANEOUS LAMPS.

Type of lamp.	Cost per B.O.T. unit.							
	1*d.*	2*d.*	3*d.*	4*d.*	5*d.*	6*d.*	7*d.*	8*d.*
Magnetite arc	0·8	1·6	2·4	3·2	4·0	4·8	5·6	6·4
Mercury vapour (ordinary)	0·4	0·8	1·2	1·6	2·0	2·4	2·8	3·2
,, (Kuch)	0·3	0·6	0·9	1·2	1·5	1·8	2·1	2·4
Moore tube	1·8	3·6	5·4	7·2	9·0	10·8	12·6	14·4

CHAPTER XII

COMPARISON OF LAMPS OF DIFFERENT TYPES

Having now discussed the various types of electric lamps separately, it is possible to make a general comparison of their merits and their suitability for different purposes. It will be convenient, in the first place, to tabulate the results already given for the different lamps in such a way that the different types can be compared one with another. In Table XXXIII. (p. 294) are given the costs of lighting per 1,000 candle-hours with different kinds of electric lamps. In order to condense this table as much as possible, typical figures have been taken for each type of lamp. As the tables which have been given in the course of the book show, considerable differences exist in the cost of lighting even with lamps of a particular kind, and the reader must refer to those tables for further particulars in the case of each lamp.

It is of interest to re-arrange this table to show the various lamps in order of merit at different costs per B.O.T. unit. As has been pointed out already, the cheapest lamp to use when energy is at one price is by no means necessarily the cheapest at a different price for energy on account of the effect of renewal costs on the total cost of the lighting. In Table XXXIV. the lamps are re-arranged in order of merit for three different prices per B.O.T. unit.

Table XXXIII.

Cost of Lighting per 1,000 Candle-hours with Various Lamps.

Type of lamp.	Consumption in watts per candle.	Price of Board of Trade unit.							
		1*d*.	2*d*.	3*d*.	4*d*.	5*d*.	6*d*.	7*d*.	8*d*.
Carbon-filament lamps [1]	3·5	5·8	9·3	12·8	16·3	19·8	23·3	26·8	30·3
Carbon-filament lamps [1]	4·0	5·0	9·0	13·0	17·0	21·0	25·0	29·0	33·0
Carbon-filament lamps [1]	4·5	5·0	9·5	14·0	18·5	23·0	27·5	32·0	36·5
Metallised - carbon - filament lamps [1]	2·8	5·7	8·5	11·3	14·1	16·9	19·7	22·5	25·3
Nernst lamps, direct-current [1]	2·1	2·5	4·6	6·7	8·8	10·9	13·0	15·1	17·2
Nernst lamps, alternating current [1]	2·4	2·8	5·2	7·6	10·0	12·4	14·8	17·2	19·6
Tantalum-filament lamps, direct-current [1]	1·7	3·2	4·9	6·6	8·3	10·0	11·7	13·4	15·1
Tantalum-filament lamps, alternating current [1]	2·1	4·3	6·4	8·5	10·6	12·7	14·8	16·9	19·0
Tungsten-filament lamps [1]	1·3	2·4	3·7	5·0	6·3	7·6	8·9	10·2	11·5
Open type arcs, retort carbons [2]	1·4	1·6	3·0	4·4	5·8	7·2	8·6	10·0	11·4
Open type arcs, soot carbons [2]	1·1	1·4	2·5	3·6	4·7	5·8	6·9	8·0	9·1
Enclosed arcs [2]	2·3	2·6	4·9	7·2	9·5	11·8	14·1	16·4	18·7
Yellow flame arcs [2]	0·4	0·6	1·0	1·4	1·8	2·2	2·6	3·0	3·4
White flame arcs [2]	0·7	0·9	1·6	2·3	3·0	3·7	4·4	5·1	5·8
Carbone arc [2]	1·0	1·2	2·2	3·2	4·2	5·2	6·2	7·2	8·2
Blondel arc [2]	0·2	0·5	0·7	0·9	1·1	1·3	1·5	1·7	1·9
Magnetite arc [3]	0·8	0·8	1·6	2·4	3·2	4·0	4·8	5·6	6·4
Mercury - vapour lamp, ordinary [3]	0·4	0·4	0·8	1·2	1·6	2·0	2·4	2·8	3·2
Mercury - vapour lamp, quartz [3]	0·3	0·3	0·6	0·9	1·2	1·5	1·8	2·1	2·4
Moore vapour lamp [3]	1·8	1·8	3·6	5·4	7·2	9·0	10·8	12·6	14·4

[1] Total cost, energy and renewals.

[2] Cost of energy and carbons, but exclusive of trimming costs and depreciation.

[3] Cost of energy only.

Table XXXIV.

Cheapest Lamp at Various Prices per B.O.T. Unit.

2*d*. per B.O.T. unit. Lamp.	Pence per 1,000 C. hrs.	4*d*. per B.O.T. unit. Lamp.	Pence per 1,000 C. hrs.	6*d*. per B.O.T. unit. Lamp.	Pence per 1,000 C. hrs.
Mercury-vapour lamp, quartz	0·6	Blondel arc	1·1	Blondel arc	1·5
Blondel arc	0·7	Mercury-vapour lamp, quartz	1·2	Mercury-vapour lamp, quartz	1·8
Mercury-vapour lamp, ordinary	0·8	Mercury-vapour lamp, ordinary	1·6	Mercury-vapour lamp, ordinary	2·4
Yellow flame arc . . .	1·0	Yellow flame arc . . .	1·8	Yellow flame arc . . .	2·6
White flame arc . . .	1·6	White flame arc . . .	3·0	White flame arc . . .	4·4
Magnetite arc . . .	1·6	Magnetite arc . . .	3·2	Magnetite arc . . .	4·8
Carbone arc	2·2	Carbone arc	4·2	Carbone arc	6·2
Soot-carbon open arc . .	2·5	Soot-carbon arc . . .	4·7	Soot-carbon arc . . .	6·9
Retort-carbon open arc . .	3·0	Retort-carbon arc . .	5·8	Retort-carbon arc . .	8·6
Moore vapour lamp . .	3·6	Tungsten lamp . . .	6·3	Tungsten lamp . . .	8·9
Tungsten lamp . . .	3·7	Moore vapour lamp . .	7·2	Moore vapour lamp . .	10·8
Nernst lamp, D.C. . . .	4·6	Tantalum lamp, D.C. . .	8·3	Tantalum lamp, D.C. . .	11·7
Enclosed arc . . .	4·9	Nernst lamp, D.C. . .	8·8	Nernst lamp, D.C. . .	13·0
Tantalum lamp, D.C. .	4·9	Enclosed arc . . .	9·5	Enclosed arc . . .	14·1
Nernst lamp, A.C. . . .	5·2	Nernst lamp, A.C. . .	10·0	Nernst lamp, A.C. . .	14·8
Tantalum lamp, A.C. . .	6·4	Tantalum lamp, A.C. . .	10·6	Tantalum lamp, A.C. .	14·8
Metallised - carbon - filament lamp	8·5	Metallised - carbon - filament lamp	14·1	Metallised - carbon - filament lamp	19·7
Carbon-filament lamp, 4·0 w./c.p.	9·0	Carbon-filament lamp, 3·5 w./c.p.	16·3	Carbon-filament lamp, 3·5 w./c.p.	23·3
Carbon-filament lamp, 3·5 w./c.p.	9·3	Carbon-filament lamp, 4·0 w./c.p.	17·0	Carbon-filament lamp, 4·0 w./c.p.	25·0
Carbon-filament lamp, 4·5 w./c.p.	9·5	Carbon-filament lamp, 4·5 w./c.p.	18·5	Carbon-filament lamp, 4·5 w./c.p.	27·5

In examining these tables, two points must be carefully borne in mind; first, that the costs are not all on quite the same basis as the cost in the case of arc lamps does not cover trimming or depreciation of the lamps, and in the case of the vapour lamps covers energy only; second, that the lamps are not all suitable for the same purposes.

With regard to the first of these points, it has already been remarked that the cost of trimming and depreciation of arc lamps is so variable that it is impossible to make any estimate that is generally applicable. In one case, for example, the lamps may be used for factory lighting, where the labour necessary for trimming is already at hand and can be employed for this purpose with practically no additional expense; in another case the lamps may be used for street lighting, and may be scattered over a large area, necessitating the employment of one or more men for several hours a day for no other purpose than re-carboning the lamps. If the lamps are burning indoors the depreciation due to wear and tear of the lamps will be slight if they are systematically overhauled and kept clean; with lamps in the open, on the other hand, the depreciation may form a very considerable item in the lighting cost. It must also be remembered that the cost of cleaning and depreciation is practically independent of the number of hours for which the lamps are used; in the case of lamps used only for a few hours each evening, and possibly not used at all in the summer, these charges are likely to amount to a higher percentage of the total cost per 1,000 candle-hours than in the case of lamps lighted from dusk till dawn all the year round. As far as the vapour lamps are concerned the maintenance costs will be low, but the cost of renewals

is at present indeterminate, and much further experience of the average life of these lamps is required before any satisfactory estimate of the importance of this factor can be formed.

The suitability of the various lamps for different purposes is a most important factor in the consideration of their relative merits. Thus the mercury-vapour arc, which is nearly the cheapest lamp to use at all prices per unit, is practically condemned on account of its colour defects. It remains to be seen whether the claims which have been made for the quartz-tube mercury-vapour lamp, both as regards colour and efficiency, are borne out in practice. Should this prove to be the case, this lamp should soon take a prominent place amongst the electric lamps suitable for use where large light sources can be employed. Compared with its most powerful rival, the flame arc, the mercury-vapour lamp possesses very marked advantages in that it is a smaller light source and is of much lower intrinsic brilliancy. The possibilities of the Moore vapour lamp are more difficult to appraise; on the actual cost of lighting this lamp does not stand particularly high, but against this must be set the great evenness and beauty of the illumination it produces, and the fact that it is possible that, in many cases, the desired illumination throughout a comparatively large space could, on account of the better distribution, be produced more cheaply by its use than by the use of some other lamp for which the cost per 1,000 candle-hours is lower.

Broadly speaking, the remaining lamps may be divided into two groups, those suitable for exterior lighting or the illumination of very large interiors, and those suitable

for interior lighting. The line of division between the two groups is, however, not very clearly marked, and it is naturally in that region which is not very distinctly within the province of one or other of the groups that the greatest difficulty exists in selecting the best lamp to use.

For exterior lighting, where large light units can be employed, as, for example, the lighting of main streets, railways, docks, etc., or for the lighting of very large interiors, it is practically only necessary to consider the various types of arc lamps since, at the present time, the claims of the vapour lamps must be regarded as not fully established. In this field it seems improbable that any of the older types of arc lamps will be able to hold out long against the flame arcs. The much greater economy of the yellow flame arc is bound before long to make it victorious over its older rivals even when the one or two serious defects which it possesses are taken into consideration. Chief amongst these is the colour of the light which it gives, which is of too marked a yellow to be called pleasant. So far, experiments in modifying this colour have not met with much success. White flame carbons are, it is true, obtainable, but, as the figures which have been given show, only at a considerable sacrifice of economy. It is probable that further experiment will overcome the difficulties which have proved insurmountable so far, and there is certainly great hope of marked improvements in this direction. Even should this hope not be realised, the future of the flame arc seems secure, for experience has certainly shown in the case of almost every advance in artificial lighting that we soon grow accustomed to colour differences if they

are not beyond all reason. When one flame arc is burning in a street of incandescent gas mantles one is impressed by its ghastly yellow glare; when the position as to numbers is reversed it is the gas mantle which gives light of a sickly green.

A defect of the flame arc lamp to which the illuminating engineer would do well to devote his attention, for it is one which it would seem could be fairly easily remedied, is the distribution of light. This is too much in the downward direction, causing too intense illumination in the space directly below the lamp and necessitating supporting the lamps at a considerable height if any serious attempt is made to produce even illumination. The Blondel flame lamp, the Jandus regenerative lamp, and other flame lamps, in which the carbons are arranged vertically, are, it is true, free from this objection, but it must be remembered that the better distribution which they possess is obtained by the sacrifice of part of the light, as has been pointed out fully for the case of the ordinary open arc in Chapter X. In the case of the flame arc with vertical carbons the amount of light cut off by the bottom carbon is less than with the ordinary open arc because the main source of light is the long luminous flame and not the crater on the upper carbon. The matter is one of considerable importance, since the bad distribution involves the wasting of a good deal of light, with the result that the economy of the flame lamp shown by the comparison on the basis of mean spherical candle-power can rarely be fully realised in practice. The difficulty should, however, be surmountable if attacked in the correct way: but just as there are still many people who think it is both artistic and satisfactory to place the

most inefficient carbon-filament lamp on the top of a glass tube and pretend it is a wax candle, so it is likely to be some time before it is generally realised even that a spherical globe which is very suitable for a light source burning at its centre is not necessarily the best thing for a light source burning at the extremity of one diameter.

The most general objection raised against the flame lamp is the "prohibitive" cost of the carbons. This objection is usually due to the circumstance that those who make it look only at the cost of carbons per year instead of at their cost per 1,000 candle-hours, for when compared on this basis the difference in cost between ordinary and flame carbons is negligible. Nevertheless, the fact that the actual cost of flame carbons is heavy is worthy of consideration, and it may be pointed out that the means of reducing this lies largely in the lamp-makers' hands. So long as the majority of lamps call for long thin carbons, probably either metal-cored or coppered, the cost is bound to remain high, since the difficulty of producing such carbons straight is great. It is not only much more difficult to manufacture a straight carbon 9 *m/m* in diameter and 24 inches long than one 18 *m/m* in diameter and only 12 inches long, but whereas in the latter case a market exists for 10, 9, 8, and even 6-inch carbons (which can most be cut from the outfalling crooked 12-inch carbons), in the former there is little or no market for shorter lengths to make use of the outfalls. For this reason the development of magazine flame lamps, using short carbons, may be looked to as affording means for considerably cheapening the cost of flame carbons, and this would be specially the case if such lamps were constructed to make use of shorter lengths in

addition to the 12-inch lengths, which could be used in the summer time when the lighting hours are few.

The objection to the cost of flame carbons has its root, possibly, in a more serious deficiency of the flame lamp. This is that at present the lamps form too large light units. Whereas the engineer who is installing a system of arc lighting is in the happy position of being able to arrange and space his lamps so as to take full advantage of the economies to be effected by the use of flame arcs, he who is only contemplating a change from ordinary to flame lamps possesses no such advantage. In the latter case the engineer must face the alternative either of re-arranging all his lamp-posts and connections or of putting the new lamps in place of the old, thereby effecting no saving in the cost of energy, incurring an increased cost for carbons, and merely giving better value for money in the way of increased illumination for which his customers, or the ratepayers, will be none too thankful when they have to pay the bill. This factor must necessarily operate strongly against the conversion of existing arc lamp installations until the use of the flame lamp has become so extended that the raising of the standard of illumination is sufficiently general to force the change. These considerations operate, moreover, against the introduction of flame lamps where the space to be illuminated is barely large enough to justify their use. For example, a shopkeeper whose supply is at 230 volts may not have sufficient frontage to warrant the use of five flame lamps, and will be consequently obliged to content himself with some less efficient light source. The remedy for these difficulties lies in the production of a satisfactory flame lamp of less candle-power, a lamp taking less than 7 amperes,

which is about the lowest limit as yet practically attained. Another way out of the second difficulty is to be found in the more extended use of alternating current, which affords the possibility by the use of transformers or choking coils of utilising single lamps without wasting the surplus energy.

The Blondel flame lamp, if the claims made on its behalf are substantiated in practice, appears to be a distinct advance on the existing types. Quite apart from the lower consumption in watts per candle the fact that the lamp is suitable for lower currents should be greatly in its favour for the reasons just given. Of the Jandus regenerative lamp it is too early at present to express any opinion.

Both these lamps serve to indicate that the possibilities of development in the flame arc are very far from being exhausted, and afford good grounds for the hope that this type of lamp may be greatly improved in the future not only in respect of the colour of its light but also in its efficiency. Additional support is given to this view by the development of the magnetite arc. Although the magnetite arc cannot compare in efficiency with the other flame arcs, it is particularly interesting as representing another solution of the same problem on very different lines. In both cases the gain in efficiency has been brought about by the substitution of an incandescent gas—a strongly selective emitter—for an incandescent solid radiating after the manner of a "black body": in both cases, therefore, the true aim of the producer of artificial light, the utilisation of a light source radiating only within the limits of the visible spectrum, has been to a certain extent realised. But though similar in general respects, in detail the two types of flame arc present important differences, the most interesting of

which is the use of the positive electrode in the one case and the negative in the other as the source of flame-producing material. Evidence has been advanced by Prof. Steinmetz to show that in the case of the magnetite arc the flame-producing material is not introduced into the arc as the result of evaporation, but is electrically projected into it after the manner of cathode rays, and Prof. Steinmetz apparently leans to the view that we have here to deal with a case of the direct electrical production of light. In the ordinary flame carbon, on the other hand, there is little question that the flame-producing materials are simply evaporated into the arc, and their greater efficiency, when used in the positive electrode, is directly explained as the result of the greater development of heat at that electrode. The evidence adduced by Prof. Steinmetz does not seem to the writer conclusive, but whether the views he advances are correct or not there is ample room for further investigation on this point, which is likely to lead to results of great theoretical interest and of great practical value.

Little need be said in reference to the ordinary open type arcs, with which the Carbone lamp must be included. The figures in Table XXXIII. show that the gain in efficiency in the Carbone arc due to the crater being fully exposed is nearly all sacrificed on account of the waste of power in the long non-luminous arc. Compared with an ordinary open arc using soot carbons (and the Carbone arc also uses this quality of carbon) the saving effected is slight and certainly not sufficient to justify conversion, though it might warrant the adoption of this type of lamp when a new installation was being put up. The Carbone lamp is, however, a very pleasing and effective light source, and in certain cases,

where colour is of importance, as for example, in lighting a picture gallery, is to be preferred to flame arcs. Stress has already been laid on the advantages of the use of higher grade carbons in open arc lamps, and more need not be said here in this connection beyond offering the advice to those who are not fortunate enough to be able to introduce flame lamps to make the best of circumstances with the means at their disposal.

The advantages of the enclosed arc are to be found in the fact that it affords a fairly efficient light source of moderately high candle-power for which the maintenance cost is low. For certain purposes, therefore, it is particularly suitable, as for the lighting of side streets or moderately large interiors. In this sphere in the past it has been able to compete successfully with the open arc; it remains to be seen whether it will be able to hold its own against the tungsten lamp. The enclosed arc possesses an advantage over the open arc in that a single lamp can be used on a 100-volt circuit with very little waste of energy, but this advantage is shared by the tungsten lamp. On the other hand, the cost of tungsten lamps of high candle-power is now, and must always remain, somewhat high; if renewals have to be made at all frequently, this factor will have considerable effect, since there is always the tendency, already referred to, to look rather at the amount of the bills than at the cost per candle-hour.

The position of the Nernst lamp is somewhat peculiar, and almost the only thing that can be found to be said in its favour is that it is the only electric lamp yet developed which is more suitable for high voltages than for low. At one time it seemed that the Nernst lamp had a great future

before it, in the realisation of which this characteristic should have been of no little importance, but it must be admitted that if it has failed, as it undoubtedly has, in making much headway against the competition of carbon-filament lamps and enclosed arcs it can have little prospect of succeeding against such a much more formidable rival as the tungsten lamp.

Of the tungsten lamp, on the other hand, it is difficult to write in anything but terms of the highest praise. Although the actual improvement in economy of the flame arc, as compared with the open arc, is almost exactly the same as that of the tungsten filament, as compared with the carbon filament, the development was much more needed in the latter case than in the former. It is no part of the object of this book to make comparisons between gas and electric lighting, but it must be pointed out that whereas the open arc could, the carbon-filament lamp could not, compete with the incandescent gas mantle on the score of price alone. It is true that recent developments of the high-pressure gas mantle have made gas lighting by this means more economical than lighting by open arcs, but these improvements have been contemporaneous with the development of the flame arc, so that once again, so far as exterior lighting is concerned, the two systems are about on a level. On the other hand, the incandescent mantle has for long held first place for cheapness for interior lighting, and in consequence the perfection of the tungsten lamp is likely to have a much greater effect on the electric lighting industry. Although, when the cost of lighting only is considered, the gas mantle is still the cheaper, the difference is no longer so marked, and the gulf is not now so broad that it cannot

be bridged by the other advantages which electric lighting possesses.

That there are disadvantages attaching to the tungsten lamp cannot be gainsaid, but one of the chief of these, that the lamps could not be run in any position, has already been overcome, and it is not too much to hope that the others will be likewise surmounted as more experience in manufacture is gained. The most serious drawback at present is the size of the light unit. The low-voltage lamps are by no means as small in candle-power as could be desired, the high-voltage are certainly too large. It is possible that it will not be long before this defect is overcome; in the meantime, it may be remarked that, as in the case of flame arcs, so here also the superiority of low voltage and of alternating supply is made evident. It is not so very long since strenuous and successful efforts were made by the supply companies for a forcible conversion from low to high-voltage supply; events have certainly tended to confirm the unwisdom of this change, and it is more than possible that a reversion to low voltage will take place. Those are most fortunate now who by virtue of an alternating supply can combine the low cost of distribution at high voltage with the advantages of lighting at low voltage.

Whether or not the tungsten-filament lamp represents the last word in metal-filament lamps is on the knees of the gods. Rumours of fresh developments are frequent, but as yet no evidence is forthcoming of any serious competitor. It must be remembered that not every lamp that goes by another name is necessarily of a different material, and up to the present, at any rate, all the promising

"competitors" of the tungsten lamp have proved to be only tungsten lamps in disguise.

The most interesting issue to watch during the next few years (apart from the possibility of the development of quite new lamps) will be the effect of the tungsten on the carbon-filament lamp. That the carbon-filament lamp will be entirely killed seems improbable, unless the tungsten lamp is soon made in high-voltage low-candle-power units. But, apart from this, there is the possibility of improvement of the carbon-filament lamp. As was pointed out in Chapter V., after twenty-five years of practical stagnation, it was suddenly discovered that the efficiency of the carbon-filament lamp could be nearly doubled by an improvement which, but for the fact that it came too late, would have been of the first importance. It seems, at any rate, feasible that the resources of the carbon-filament lamp are not yet exhausted and that we shall ultimately find the best filament for an incandescent lamp in the only element which we have not yet succeeded in melting.

A word may be said here in reference to the general question of lighting by incandescent lamps. In Chapter V. the unsatisfactory condition of affairs as regards the different voltages for which the lamp-maker has to supply lamps was commented upon, and it was remarked that the remedy was simple. Just as a certain degree of co-operation between the arc-lamp maker and the carbon manufacturer is desirable if the former wishes for cheap carbons, so a similar co-operation between the supply engineer and the lamp-maker would lead to both the cheapening and the improving of incandescent lamps. Very much may be said in favour of the supply engineer supplying his customers with

light instead of energy, providing and maintaining the lamps himself, as is done very widely in America, and as the gas companies do here with incandescent gas lighting. The *pros* and *cons* of this proposal cannot be discussed here, but, even without going to this extreme, further co-operation than exists at present would be a very great advantage to the industry. In this respect such a step as that made by drawing up a standard specification for glow lamps can only be regarded as retrograde since it must increase rather than diminish the difficulties under which the manufacturer works. Because a lamp which is manufactured with the view of being a 100-volt 16 candle-power lamp turns out at the end of the numerous processes through which it passes best suited for 95 volts it does not follow that it is a bad lamp fit only for the scrap-heap. Any co-operation between users and makers which would lead to the profitable utilisation of such "wasters" could only result in benefit to all concerned. It should always be remembered that an incandescent lamp is not like an electrical instrument; that where the one is made in tens the other is made in tens of thousands; and that an accuracy and uniformity which is desirable, or even necessary, in the one case may be only harmful in the other: facts which are so often forgotten that it is common to hear or see a particular make of lamp praised or condemned on the result of a test carried out with extreme accuracy on a half-dozen of lamps, which is quite valueless when compared with a test made with one tenth the care on ten times the number of lamps.

Conclusion.

The producer of electric light may have reason to feel ashamed before his competitor in the gas industry, but

he cannot lay the blame at the door of the maker of electric lamps. Whatever their defects in other respects, there is not one of the numerous lamps described in this book which is not far more efficient as a light source than any other kind of practical artificial illuminant. According to figures recently published by the Imperial Continental Gas Association, the least efficient of the electric lamps was about twice, and the most efficient about twenty times, as good as a light source as the best of the gas lamps. The gas engineer, fortunate in a supply of cheap energy, is able with lavish waste to produce a cheap light; the electric lamp-maker, utilising an expensive form of energy, is obliged to husband his resources to the utmost. Gratifying as this reflection may be, a valuable corrective to any false pride is to be found in the remarkable inefficiency of the lamp-maker's best results. It has been mentioned in Chapter II. that the luminous efficiency of electric lamps is from 2—20 per cent. The most recent researches, by Drysdale and Jolley,[1] show that the mechanical equivalent of white light is about 0·08 watts per candle or even less. This figure has only to be compared with those in the first column in Table XXXIII. to show how far off perfection still lies. It has taken nearly a century to reduce the consumption in arc lamps from about 1·5 to 0·2 watts per candle, and over a quarter of a century to reduce the consumption in incandescent lamps from about 5·0 to 1·3 watts per candle; how many years will it be before the figures now reached are reduced to 0·08 watts per candle? The electrical engineer can have

[1] See a series of articles by Dr. Drysdale running through Vol. I. of *The Illuminating Engineer*, which summarise the work done in this connection.

no cause for complaint that all fields of research are exhausted.

In conclusion, the writer would like to quote a paragraph from an article which he recently contributed to *Nature*:[1] "Attention may be directed to the honourable position occupied by this country in the development of electric lamps. A little more than a century ago an English scientist, Sir Humphry Davy, discovered the electric arc. Thirty years ago an English inventor, Sir Joseph Swan, shared with an American, Edison, the distinction of overcoming the difficulties attendant upon the production of an incandescent electric lamp of small candle-power. With these two names England's connection with the development of electric lamps begins and ends. The first satisfactory arc-lamp carbons were made by Carré (France). The invention of the cored carbon is due to Siemens (Germany), the practical realisation of flame carbons to Bremer (Germany), and their further development to the Continental manufacturers and to Blondel (France). The magnetite arc has been developed by Steinmetz and the General Electric Company of America. The mercury arc was shown to be practical by Arons (Germany), and was perfected by Cooper-Hewitt (America). Its latest development is due to the firm of Heraeus (Germany). The vacuum-tube lamp we owe to McFarlane Moore (America). In incandescent lighting the only radical improvement which has been effected in the carbon-filament is the metallised filament of the General Electric Company of America. The Nernst lamp is due to Prof. Nernst and the Allgemeine Elektricitäts Gesellschaft of Germany. The first metal-filament lamp

[1] *Nature*, Vol. LXXVIII., p. 185, June 25th, 1908.

was the osmium lamp of Welsbach (Germany), which was followed by the tantalum lamp of Siemens (Germany) and the tungsten lamp which was perfected by Welsbach (Germany), Just and Hanaman (Austria), and Kuzel (Austria)." If this book should help to fire any enthusiast to remove this reproach from England, and to make one more step towards the goal of the 0·08 watt per candle electric lamp it will not have been written in vain.

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BRADBURY, AGNEW, & CO. LD., PRINTERS, LONDON AND TONBRIDGE.

Coal. By JAMES TONGE, M.I.M.E., F.G.S., etc. (Lecturer on Mining at Victoria University, Manchester). With 46 Illustrations, many of them showing the Fossils found in the Coal Measures.

LIST OF CONTENTS: History. Occurrence. Mode of Formation of Coal Seams. Fossils of the Coal Measures. Botany of the Coal-Measure Plants. Coalfields of the British Isles. Foreign Coalfields. The Classification of Coals. The Valuation of Coal. Foreign Coals and their Values. Uses of Coal. The Production of Heat from Coal. Waste of Coal. The Preparation of Coal for the Market. Coaling Stations of the World. Index.

This book on a momentous subject is provided for the general reader who wishes accurate knowledge of Coal, its origin, position and extent, and its economical utilization and application.

Iron and Steel. By J. H. STANSBIE, B.Sc. (Lond.), F.I.C. With 86 Illustrations.

LIST OF CONTENTS: Introductory. Iron Ores. Combustible and other materials used in Iron and Steel Manufacture. Primitive Methods of Iron and Steel Production. Pig Iron and its Manufacture. The Refining of Pig Iron in Small Charges. Crucible and Weld Steel. The Bessemer Process. The Open Hearth Process. Mechanical Treatment of Iron and Steel. Physical and Mechanical Properties of Iron and Steel. Iron and Steel under the Microscope. Heat Treatment of Iron and Steel. Electric Smelting. Special Steels. Index.

The aim of this book is to give a comprehensive view of the modern aspects of iron and steel, together with a sufficient account of its history to enable the reader to follow its march of progress. The methods of producing varieties of the metal suitable to the requirements of the engineer, foundryman and mechanician are described so that the worker may learn the history of the material he is handling.

Natural Sources of Power. By ROBERT S. BALL, B.Sc., A.M.Inst.C.E. With 104 Diagrams and Illustrations.

CONTENTS: Preface. Units with Metric Equivalents and Abbreviations. Length and Distance. Surface and Area. Volumes. Weights or Measures. Pressures. Linear Velocities, Angular Velocities. Acceleration. Energy. Power. Introductory Water Power and Methods of Measuring. Application of Water Power to the Propulsion of Machinery. The Hydraulic Turbine. Various Types of Turbine. Construction of Water Power Plants. Water Power Installations. The Regulation of Turbines. Wind Pressure, Velocity, and Methods of Measuring. The Application of Wind Power to Industry. The Modern Windmill. Constructional Details. Power of Modern Windmills. Appendices A, B, C. Index.

Two departments of Engineering and their applications to industry form the subject of this volume: the "natural" sources of water

and wind power which supply mechanical energy without any intermediate stage of transformation. Most people will be surprised at the extent to which these natural power producers are used. The widespread application of water power is generally known, but it is interesting to learn that the demand for windmills was never so great as it is to-day, and there are signs of abnormal expansion in the direction of their useful application in the great agricultural countries of the world. Though primarily of importance to the engineer, this work will be of great interest to every manufacturer who in economizing his means of power production can take the natural forces that lie to his hand and harness them in his service. The author is the son of Sir Robert Ball, the eminent mathematician and astronomer.

Liquid and Gaseous Fuels, and the Part they play in Modern Power Production. By Professor VIVIAN B. LEWES, F.I.C., F.C.S., Prof. of Chemistry, Royal Naval College, Greenwich. With 54 Illustrations.

LIST OF CONTENTS: Lavoisier's Discovery of the Nature of Combustion, etc. The Cycle of Animal and Vegetable Life. Method of determining Calorific Value. The Discovery of Petroleum in America. Oil Lamps, etc. The History of Coal Gas. Calorific Value of Coal Gas and its Constituents. The History of Water Gas. Incomplete Combustion. Comparison of the Thermal Values of our Fuels, etc. Appendix. Bibliography. Index.

The subject of this book has, during the last decade, assumed such importance that it is hoped this account of the history and development of the use of various forms of combustible liquids and gases for the generation of energy may do some service in its advancement.

Electric Power and Traction. By F. H. DAVIES, A.M.I.E.E. With 66 Illustrations.

LIST OF CONTENTS: Introduction. The Generation and Distribution of Power. The Electric Motor. The Application of Electric Power. Electric Power in Collieries. Electric Power in Engineering Workshops. Electric Power in Textile Factories. Electric Power in the Printing Trade. Electric Power at Sea. Electric Power on Canals. Electric Traction. The Overhead System and Track Work. The Conduit System. The Surface Contact System. Car Building and Equipment. Electric Railways. Glossary. Index.

The majority of the allied trades that cluster round the business of electrical engineering are connected in some way or other with its power and traction branches. To members of such trades and callings, to whom some knowledge of applied electrical engineering is desirable if not strictly essential, the book is particularly intended to appeal. It deals almost entirely with practical matters, and enters to some extent into those commercial considerations which in the long run must overrule all others.

Town Gas and its Uses for the Production of Light, Heat, and Motive Power. By W. H. Y. Webber, C.E. With 71 Illustrations.

List of Contents: The Nature and Properties of Town Gas. The History and Manufacture of Town Gas. The Bye-Products of Coal Gas Manufacture. Gas Lights and Lighting. Practical Gas Lighting. The Cost of Gas Lighting. Heating and Warming by Gas. Cooking by Gas. The Healthfulness and Safety of Gas in all its uses. Town Gas for Power Generation, including Private Electricity Supply. The Legal Relations of Gas Suppliers, Consumers, and the Public. Index.

The "country," as opposed to the "town," has been defined as "the parts beyond the gas lamps." This book provides accurate knowledge regarding the manufacture and supply of town gas and its uses for domestic and industrial purposes. Few people realize the extent to which this great industry can be utilized. The author has produced a volume which will instruct and interest the generally well informed but not technically instructed reader.

Electro-Metallurgy. By J. B. C. Kershaw, F.I.C. With 61 Illustrations.

Contents: Introduction and Historical Survey. Aluminium. Production. Details of Processes and Works. Costs. Utilization. Future of the Metal. Bullion and Gold. Silver Refining Process. Gold Refining Processes. Gold Extraction Processes. Calcium Carbide and Acetylene Gas. The Carbide Furnace and Process. Production. Utilization. Carborundum. Details of Manufacture. Properties and Uses. Copper. Copper Refining. Descriptions of Refineries. Costs. Properties and Utilization. The Elmore and similar Processes. Electrolytic Extraction Processes. Electro-Metallurgical Concentration Processes. Ferro-alloys. Descriptions of Works. Utilization. Glass and Quartz Glass. Graphite. Details of Process. Utilization. Iron and Steel. Descriptions of Furnaces and Processes. Yields and Costs. Comparative Costs. Lead. The Salom Process. The Betts Refining Process. The Betts Reduction Process. White Lead Processes. Miscellaneous Products. Calcium. Carbon Bisulphide. Carbon Tetra-Chloride. Diamantine. Magnesium. Phosphorus. Silicon and its Compounds. Nickel. Wet Processes. Dry Processes. Sodium. Descriptions of Cells and Processes. Tin. Alkaline Processes for Tin Stripping. Acid Processes for Tin Stripping. Salt Processes for Tin Stripping. Zinc. Wet Processes. Dry Processes. Electro-Thermal Processes. Electro-Galvanizing. Glossary. Name Index.

The subject of this volume, the branch of metallurgy which deals with the extraction and refining of metals by aid of electricity, is becoming of great importance. The author gives a brief and clear account of the industrial developments of electro-metallurgy, in language that can be understood by those whose acquaintance with either

chemical or electrical science may be but slight. It is a thoroughly practical work descriptive of apparatus and processes, and commends itself to all practical men engaged in metallurgical operations, as well as to business men, financiers, and investors.

Radio-Telegraphy. By C. C. F. MONCKTON, M.I.E.E. With 173 Diagrams and Illustrations.

CONTENTS: Preface. Electric Phenomena. Electric Vibrations. Electro-Magnetic Waves. Modified Hertz Waves used in Radio-Telegraphy. Apparatus used for Charging the Oscillator. The Electric Oscillator: Methods of Arrangement, Practical Details. The Receiver: Methods of Arrangement, The Detecting Apparatus, and other details. Measurements in Radio-Telegraphy. The Experimental Station at Elmers End: Lodge-Muirhead System. Radio-Telegraph Station at Nauen: Telefunken System. Station at Lyngby: Poulsen System. The Lodge-Muirhead System, the Marconi System, Telefunken System, and Poulsen System. Portable Stations. Radio-Telephony. Appendices: The Morse Alphabet. Electrical Units used in this Book. International Control of Radio-Telegraphy. Index.

The startling discovery twelve years ago of what is popularly known as Wireless Telegraphy has received many no less startling additions since then. The official name now given to this branch of electrical practice is Radio-Telegraphy. The subject has now reached a thoroughly practicable stage, and this book presents it in clear, concise form. The various services for which Radio-Telegraphy is or may be used are indicated by the author. Every stage of the subject is illustrated by diagrams or photographs of apparatus, so that, while an elementary knowledge of electricity is presupposed, the bearings of the subject can be grasped by every reader. No subject is fraught with so many possibilities of development for the future relationships of the peoples of the world.

India-Rubber and its Manufacture, with Chapters on Gutta-Percha and Balata. By H. L. TERRY, F.I.C., Assoc.Inst.M.M. With Illustrations.

LIST OF CONTENTS: Preface. Introduction: Historical and General. Raw Rubber. Botanical Origin. Tapping the Trees. Coagulation. Principal Raw Rubbers of Commerce. Pseudo-Rubbers. Congo Rubber. General Considerations. Chemical and Physical Properties. Vulcanization. India-rubber Plantations. India-rubber Substitutes. Reclaimed Rubber. Washing and Drying of Raw Rubber. Compounding of Rubber. Rubber Solvents and their Recovery. Rubber Solution. Fine Cut Sheet and Articles made therefrom. Elastic Thread. Mechanical Rubber Goods. Sundry Rubber Articles. India-rubber Proofed Textures. Tyres. India-rubber Boots and Shoes. Rubber for Insulated Wires. Vulcanite Contracts for India-rubber Goods.

The Testing of Rubber Goods. Gutta-Percha. Balata. Bibliography. Index.

Tells all about a material which has grown immensely in commercial importance in recent years. It has been expressly written for the general reader and for the technologist in other branches of industry.

Glass Manufacture. By WALTER ROSENHAIN, Superintendent of the Department of Metallurgy in the National Physical Laboratory, late Scientific Adviser in the Glass Works of Messrs. Chance Bros. and Co. With Illustrations.

CONTENTS: Preface. Definitions. Physical and Chemical Qualities. Mechanical, Thermal, and Electrical Properties. Transparency and Colour. Raw materials of manufacture. Crucibles and Furnaces for Fusion. Process of Fusion. Processes used in Working of Glass. Bottle. Blown and Pressed. Rolled or Plate. Sheet and Crown. Coloured. Optical Glass: Nature and Properties, Manufacture. Miscellaneous Products. Appendix. Bibliography of Glass Manufacture. Index.

This volume is for users of glass, and makes no claim to be an adequate guide or help to those engaged in glass manufacture itself. For this reason the account of manufacturing processes has been kept as non-technical as possible. In describing each process the object in view has been to give an insight into the rationale of each step, so far as it is known or understood, from the point of view of principles and methods rather than as mere rule of thumb description of manufacturing manipulations. The processes described are, with the exception of those described as obsolete, to the author's definite knowledge, in commercial use at the present time.

Precious Stones. By W. GOODCHILD, M.B., B.Ch. With 42 Illustrations. **With a Chapter on Artificial Stones.** By ROBERT DYKES.

LIST OF CONTENTS: Introductory and Historical. Genesis of Precious Stones. Physical Properties. The Cutting and Polishing of Gems. Imitation Gems and the Artificial Production of Precious Stones. The Diamond. Fluor Spar and the Forms of Silica. Corundum, including Ruby and Sapphire. Spinel and Chrysoberyl. The Carbonates and the Felspars. The Pyroxene and Amphibole Groups. Beryl, Cordierite, Lapis Lazuli and the Garnets. Olivine, Topaz, Tourmaline and other Silicates. Phosphates, Sulphates, and Carbon Compounds.

An admirable guide to a fascinating subject.

Patents, Designs and Trade Marks: The Law and Commercial Usage. By KENNETH R. SWAN, B.A. (Oxon.), of the Inner Temple, Barrister-at-Law.

CONTENTS: Table of Cases Cited—*Part I.—Letters Patent.* Introduction. General. Historical. I., II., III. Invention, Novelty, Subject Matter, and Utility the Essentials of Patentable Invention. IV. Specification. V. Construction of Specification. VI. Who May Apply for a Patent. VII. Application and Grant. VIII. Opposition. IX. Patent Rights. Legal Value. Commercial Value. X. Amendment. XI. Infringement of Patent. XII. Action for Infringement. XIII. Action to Restrain Threats. XIV. Negotiation of Patents by Sale and Licence. XV. Limitations on Patent Right. XVI. Revocation. XVII. Prolongation. XVIII. Miscellaneous. XIX. Foreign Patents. XX. Foreign Patent Laws: United States of America. Germany. France. Table of Cost, etc., of Foreign Patents. APPENDIX A.—1. Table of Forms and Fees. 2. Cost of Obtaining a British Patent. 3. Convention Countries. *Part II.—Copyright in Design.* Introduction. I. Registrable Designs. II. Registration. III. Marking. IV. Infringement. APPENDIX B.—1. Table of Forms and Fees. 2. Classification of Goods. *Part III.—Trade Marks.* Introduction. I. Meaning of Trade Mark. II. Qualification for Registration. III. Restrictions on Registration. IV. Registration. V. Effect of Registration. VI. Miscellaneous. APPENDIX C.—Table of Forms and Fees. INDICES. 1. Patents. 2. Designs. 3. Trade Marks.

This is the first book on the subject since the New Patents Act. Its aim is not only to present the existing law accurately and as fully as possible, but also to cast it in a form readily comprehensible to the layman unfamiliar with legal phraseology. It will be of value to those engaged in trades and industries where a knowledge of the patenting of inventions and the registration of trade marks is important. Full information is given regarding patents in foreign countries.

The Book; Its History and Development. By CYRIL DAVENPORT, V.D., F.S.A. With 7 Plates and 126 Figures in the text.

LIST OF CONTENTS: Early Records. Rolls, Books and Book bindings. Paper. Printing. Illustrations. Miscellanea. Leathers. The Ornamentation of Leather Bookbindings without Gold. The Ornamentation of Leather Bookbindings with Gold, Bibliography. Index.

The romance of the Book and its development from the rude inscriptions on stone to the magnificent de Luxe tomes of to-day have never been so excellently discoursed upon as in this volume. The history of the Book is the history of the preservation of human thought. This work should be in the possession of evey book lover.